2001

Preliminary analysis of factors controlling virus transport in a floodplain aquifer western Montana

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DATE 7/11/01

PRELIMINARY ANALYSIS OF FACTORS CONTROLLING VIRUS TRANSPORT IN A FLOODPLAIN AQUIFER, WESTERN MONTANA

By

Jennifer M. Bushur

B.A. The University of Montana, 1998

presented in partial fulfillment of the requirements

for the degree of

Master of Science

The University of Montana

2001

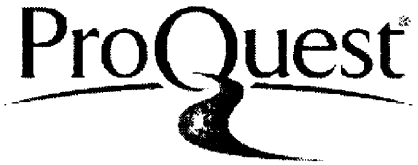
Approved by:

Chairman

Dean, Graduate School

7-19-01

Date



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Bushur, Jennifer M. M.S., July 2001 **Geology**

Preliminary Analysis of Factors Controlling Virus Transport in a Floodplain Aquifer, Western Montana

Chairman: Dr. William W. Woessner

Waterborne pathogens can cause a variety of illnesses, so it is crucial to determine the principal parameters controlling virus transport and fate in groundwater. This research has become a priority since the Environmental Protection Agency proposed its Groundwater Disinfection Rule, which protects public groundwater supply systems from microbial contamination. The primary focus of this research was to characterize the hydrologic and physical properties of the aquifer, along with specific controls on virus transport in a cold-water, highly conductive aquifer. An unconfined floodplain aquifer near Missoula, Montana was instrumented with 59 monitoring wells and five injection wells. Natural gradient tracer tests were conducted using rhodamine WT dye, sodium bromide and the bacteriophage MS-2. Velocity estimates for the bromide ranged from 20 to 92 ft/d, with hydraulic conductivity values of 12,300 to 28,400 ft/d. The MS-2 breakthrough peak not only arrived sooner than the bromide, but at higher relative concentrations, indicating preferential flow and possible pore exclusion occurred. Although the MS-2 tracer test showed a 4-log virus attenuation between 66 and 77 feet from the injection site, caution should be used when determining if the pathogen level is low enough to no longer pose a significant health risk.

Acknowledgements

The National Water Resources Institute and the U. S. Environmental Protection Agency funded this project, and the subsequent research of other students who followed at the site.

First of all, I would like to thank Dennis Workman and his staff at Montana Fish, Wildlife and Parks for allowing me to establish the study area at Erskine Fishing Access. Dan DeBorde, who always made time for his students despite his busy schedule, spent endless days and nights in the microbiology laboratory, assisted by Pat Ball. Lynn Biegelsen analyzed numerous tracer tests and kept outstanding records. The office staff Christine Foster and, especially, Loreene Skeel helped with all things administrative and ensured I remained a viable student.

Don Winston and Bill Holben were generous in their time and efforts for agreeing to join my thesis committee at a very late stage. I am grateful for their insightful and constructive suggestions. My committee chair, Bill Woessner, while very exuberant in his editing efforts during the final stages of this thesis, was also proactive in steering the way through the field studies. His input and time over the years are greatly appreciated. Finally, the assistance of Don Kammerer was invaluable in helping me through the first arduous months in the field, and without whose support I would not have continued.

Table of Contents

List of Tables

List of Figures

1. Introduction

Understanding the behavior and transport of microorganisms in groundwater systems is important when designing monitoring programs, and implementing and assessing bioremediation measures. Although groundwater is generally viewed as relatively pristine, it was considered responsible for approximately 42% of all waterborne diseases in the United States before 1990, most involving sewage from septic tanks (Gerba and Rose 1990). However, more recent data from the Environmental Protection Agency (EPA) and the Center for Disease Control (CDC) indicate that 81% of waterborne outbreaks reported between 1971 and 1996 were caused by untreated or inadequately disinfected or filtered groundwater (USEPA 2000). Waterborne pathogens can cause a variety of illnesses ranging from mild diarrhea to heart disease and death, so it is crucial to determine the principal parameters controlling pathogen transport and fate. This research has become a priority in recent years since the EPA proposed its Groundwater Disinfection Rule (GWDR). The new regulation identifies public groundwater systems at risk from fecal contamination, and attempts to insure adequate measures are taken to remove or inactivate pathogens in the drinking water provided by these systems. Disinfecting public water supply systems is mandatory, unless potential sources are a safe distance from wells, such that "natural disinfection" occurs before pathogens reach wellheads. The GWDR goal is to reduce the risk of infection by achieving a 4-log inactivation or removal of viruses in source water (USEPA 2000). At this time, the Groundwater Rule is under review and scheduled to be issued as a final regulation in August or September 2001 (USEPA 2001).

Many attempts have been made to find tracers that would accurately mimic virus behavior in groundwater. Not only are the organisms themselves difficult to detect and monitor, there is also the danger of spreading pathogens during field experiments. Bacteriophages, viruses that only infect bacteria, are frequently used because of size, lack of human pathogenicity, and ease of assay (Corapcioglu and Haridas 1985). In this study, the bacteriophage MS-2 was chosen to emulate human enteric virus transport. Powelson et al (1990) report little MS-2 adsorption or inactivation under saturated conditions; therefore its behavior would be considered to represent worst-case, virus transport scenario.

The mechanics of viral transport and survival are pertinent in determining how far and how quickly a pathogen may travel from its source. These are controlled not only by the physical properties of the aquifer, but also by characteristics of the microbe itself. Groundwater velocities influence microbial transport, along with aquifer stratigraphy, hydraulic conductivity, and heterogeneities in the aquifer. Pathogen transport is also affected by aquifer properties such as grain size and shape, recharge events, depth to groundwater and extent of soil saturation (Zachara 1990). Adelman et al (1998) list five mechanisms involved in microbial transport in the saturated zone: adsorption, advection, die-off, dispersion and filtration. Depending on the location and type of microorganism, survival varies with particle stability, surface chemistry, water chemistry and temperature.

Of particular interest in this study is how the complexities of coarse-grained fluvial aquifers influence the transport and fate of viruses and solutes (Leibundgut et al 1992). Fluvial depositional environments are often complex with great variability in

aquifer structure, resulting in both vertical and horizontal heterogeneities. Coarse-grained systems present special challenges when attempting to predict the behavior of ionic or viral tracers. Preferential flow, complex depositional structures and variations in velocity complicate predicting tracer behavior (Harvey and Gorelick 2000, Poeter and Gaylord 1990).

The primary purpose of this research is to characterize physical and virus-specific controls on virus transport in a cold-water, highly conductive, floodplain aquifer. Specifically, the work will:

1) Describe hydrologic systems at the study site, using standard water-level interpretation and aquifer testing methods.

2) Characterize the physical and geochemical properties of a coarse, shallow floodplain aquifer system including the stratigraphy, porosity, grain-size, water chemistry, and hydraulic conductivity (K) distributions.

3) Conduct rhodamine WT (RWT) dye and sodium bromide tracer tests to establish groundwater flow paths, velocity distribution and dispersion properties.

4) Conduct an MS-2 bacteriophage (virus) tracer test to examine factors controlling virus transport and fate.

The relationship between the behavior of the conservative tracers and bacteriophage was used to examine how both the heterogeneities in the aquifer materials and virus-specific features impacted the resulting tracer distributions.

The next section of this paper will contain a general description of viruses, along with environmental features and factors that control transport in soil and groundwater systems, followed by sections describing methods, results and discussion.

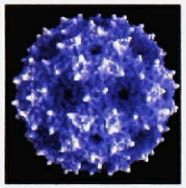
2.0 Virus Properties and Factors Influencing Transport

Viruses are single or double strands of nucleic acid (DNA or RNA) surrounded by a protein coat called a capsid. They are not cells and lack a metabolism, needing a host cell in order to replicate. Virus particles range from 0.02 to 0.3 microns in size, are strongly negatively charged at high pH, and are positively charged at a low pH (Brock et al 1994). As time progresses, viruses can lose the ability to infect host cells through a process called inactivation, caused by extremes in pH, disruption of coat proteins, and degradation of nucleic acids. Bacteriophages, viruses that target specific bacteria as hosts, are comparatively large in size and are non-pathogenic to humans. While bacteria can usually be seen and sometimes identified under a light microscope, virions and bacteriophages must be viewed with electron microscopy. Figure 1 illustrates the relative sizes of viruses, sand and clay.

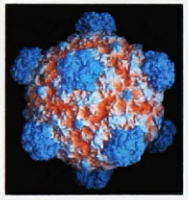
2.1 Virus Behavior and Persistence

Non-pathogenic bacteria and bacteriophages are found in many environments, including sediments more than 600 feet deep (Bradford and Gerba 1990), but it is microbes threatening human health that pose problems in groundwater. Allen (1981) reports aquifers as deep as 490 feet contaminated by septic tank leachfields.

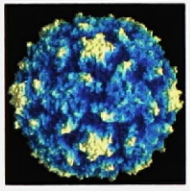
Virus survival in soil bears a significant relationship to groundwater contamination, as the microbes may migrate long distances before entering the groundwater. Viruses commonly enter groundwater by traveling down through the soil, and survival probability depends on the location and type of microorganisms, and can vary greatly with particle stability, surface chemistry and water chemistry. Other factors



MS2



ØX174



Polio 1

Particle	Average diameter (µm)
MS2	0.027
ØX174	0.023
Polio 1	0.030
Rotavirus	0.070
Clay	< 2.0
Sand Grains	62.5 - 2,000

Figure 1. Relative sizes of viruses, clay and sand.

affecting microbial transport into the aquifer are rainfall or artificial recharge events, depth to groundwater and extent of soil saturation. Additionally, salt concentration, pH, organic matter, and soil content control migration of microorganisms in groundwater systems.

Fate of viruses near the surface depends largely on soil properties. Survival rates increase with high soil moisture content and organic matter, low temperatures and high pH (Canter and Knox, 1984). Sunlight is detrimental, and while aerobic soil organisms adversely affect virion survival, anaerobic organisms have no effect (Yates and Gerba 1985, Canter and Knox 1984). Keswick and Gerba (1980) report virus penetrating 98 feet through several soil profiles, and traveling 297 feet laterally, and can remain activated in the soil for 12 days to 6 months (Kowai 1985). Water flowing through the soil column can reactivate adsorbed viruses, increasing the potential of movement into the groundwater (Wang et al 1981).

Temperature may be the single most important factor in determining virus inactivation rates in groundwater, with lower temperatures favoring longer survival times (Kutz and Gerba 1988, Gerba and Bales 1990). Nasser et al (1993) also show temperature as the most well defined factor affecting virus survival in natural water, with viruses remaining infectious for several months at near-freezing temperatures. Kukkula et al (1997) discuss cold climates enabling extended enterovirus survival in river water, including 34% of enteric viruses surviving in an ice-covered Alaska river flowing 197 miles in seven days. In a comparing virus survival in freshwater, Kutz and Gerba (1988) found coliphage to possess the slowest inactivation rate in groundwater.

Under oligotrophic conditions, where the water is generally colder and has a higher oxygen content, viruses may maintain population levels for at least seven days. After that, Pekdeger and Matthess (1983) approximate viruses and bacteria decline at a negative exponential rate with the equation:

$$C_t = C_o e^{-\lambda(t-to)}$$

Where:

t = time
$t \geq t_o$ and $t_o \leq 7$ days
C_o = initial concentration
C_t = concentration at time t
λ = elimination constant $(\ln 2)/(\tau_{1/2})$
$\tau_{1/2}$ = microbe half-life, generally between 1 and 20 days

From this equation, viruses and bacteria are inactivated very rapidly at first, and then may exist in small quantities in groundwater for a long time.

Viruses can persist from 2 days to 6 months in groundwater (Kowai 1985). Survival time of viruses in groundwater varies for specific species, and different groundwater environments, which are influenced by temperature and water chemistry. Sometimes, adsorption to other particles can render a virus more resistant to inactivation, perhaps by stabilizing coat proteins or inactivating antiviral enzymes, though the exact mechanism is unclear (Grant et al 1993).

2.2 Transport and Adsorption

After reaching the vadose zone, viruses may travel through the groundwater. Physical factors controlling viral transport are pertinent in determining how far and how quickly a pathogen may travel from its source. Groundwater velocities drive transport and can vary greatly from one aquifer to another. Velocity distributions are affected by

sediment grain size and shape, the presence of fractures and karstic geology, and the distribution of hydraulic conductivity, porosity, and hydraulic gradient.

When a microbe reaches the groundwater, four events can occur: suspension in fluid, sedimentation and filtration, reversible adsorption, or irreversible adsorption. If the organisms remain suspended, virus transport occurs by turbulent convection and particle diffusion (Grant et al 1993). According to Corapcioglu and Haridas (1985), sedimentation is generally not significant since viruses are neutrally buoyant and tend not to settle. Microorganism transport can be limited by mechanical filtration if the pore size of aquifer material is comparable with that of the microorganisms. Coincidentally, filtration is usually not a factor in restricting the microbes, since in a free form they are relatively much smaller than any pore openings.

Adsorption, a process in which a virus adheres to the surface of another particle, is the major limiting, virus-specific factor controlling transport of microorganisms through aquifers. Adsorption is influenced by a combination of electrostatic and Van der Waals forces, and hydrophobic reactions between microbes and soil particles; while desorption commonly occurs due to changes in the ionic strength of the water (Yates et al 1991). The attachment process takes place rapidly, usually within two hours, within a pH range of 4.0 to 10.0 (Matthess et al 1988, Pekdeger and Matthess 1986). Bacteria and viruses are typically associated with small particles with large surface areas, such as clays, even when a greater number of coarse particles are available. Moore, et al (1975) report enhanced virus adsorption in the presence of cations, which decrease the repulsive forces of the grain surfaces. Viruses commonly adsorb to other particulates in the groundwater and saturated zone, and are either retained in suspension, filtered, or

transported farther through the system in this state. Viruses also sorb to the surfaces of the aquifer matrix. The microbes may then desorb from the adherent particulates, enabling viruses to travel even farther through groundwater systems.

No single pattern of adsorption is congruent with all viruses. The differences in virus adsorption are probably due to protein configurations on the outer capsid influencing the net charge on the virus, which is dependent on the pH of the surrounding medium (Gerba et al 1981). The net charge of a virus particle is negative at a pH above neutral, and the sand, clay and organic materials of an aquifer are also negatively charge at a pH above 7 (Gerba and Bitton 1984). However, Gerba and Bitton also (1984) cautioned that virus adsorption is not necessarily at a minimum at alkaline pH, due to other factors: the pH of the medium is not necessarily the pH at the virus surface; and viruses display different isoelectric points and isoelectric points vary with virus type and strain.

Viral adsorption to solids enhances virus survival, resulting in resistance to inactivation, but it also increases the chance of halting virus transport. However, if a virus is desorbed, it may be able to travel far through the porous medium due to its small size. Zachara (1990) believes that other hydrologic properties of the system may be involved, but are generally ignored; for example, the correlations between texture and microorganisms could also be a reflection of hydraulic conductivity and pore diameter, as well as surface area. Many properties are related, making it difficult to analyze what the primary influencing factors are in the virus adsorption process.

Methods to model virus transport are limited by a lack of quantitative information on microbe-media interactions, and microorganisms differ in character, thus generalizing

their behavior is difficult. Human viruses generally cannot be used in the field due to possible health risks, so bacteriophage tracers that exhibit similar properties are alternatives. The MS-2 bacteriophage was used in this study since it is non-pathogenic to humans, but is similar to human enteric viruses in size, structure, movement and survival. MS-2 has a diameter of approximately .027 microns and an isoelectric point of pH 3.9 (Powelson et al 1990). MS-2 and Hepatitis A viruses illustrate similar free chlorine inactivation rates, and the MS-2 coliphage concentrations were well correlated with *E. coli* and enterococcin field samples (Handzel et al 1990). The bacteriophage has been used as a reliable viral indicator and also as an indicator of fecal contamination (Nasser et al 1993, Powelson et al 1993).

3.0 Methods

3.1 Site Selection

Selecting a suitable study area involved comparing potential sites on the Clark Fork River floodplain, using the following criteria: the presence of a coarse gravel, highly conductive groundwater system with a shallow water table; an accessible, expansive area to allow instrumentation of a flow field several hundred feet long; isolated in location to avoid potential contamination of existing water-supply wells; and physical access for an extended period of time, so that a number of experiments could be conducted.

An area on the eastern side of Erskine Fishing Access measuring 780 feet by 850 feet was chosen for the study site. It is located approximately 20 miles west of Missoula, Montana, on the Clark Fork River floodplain (Figure 2).

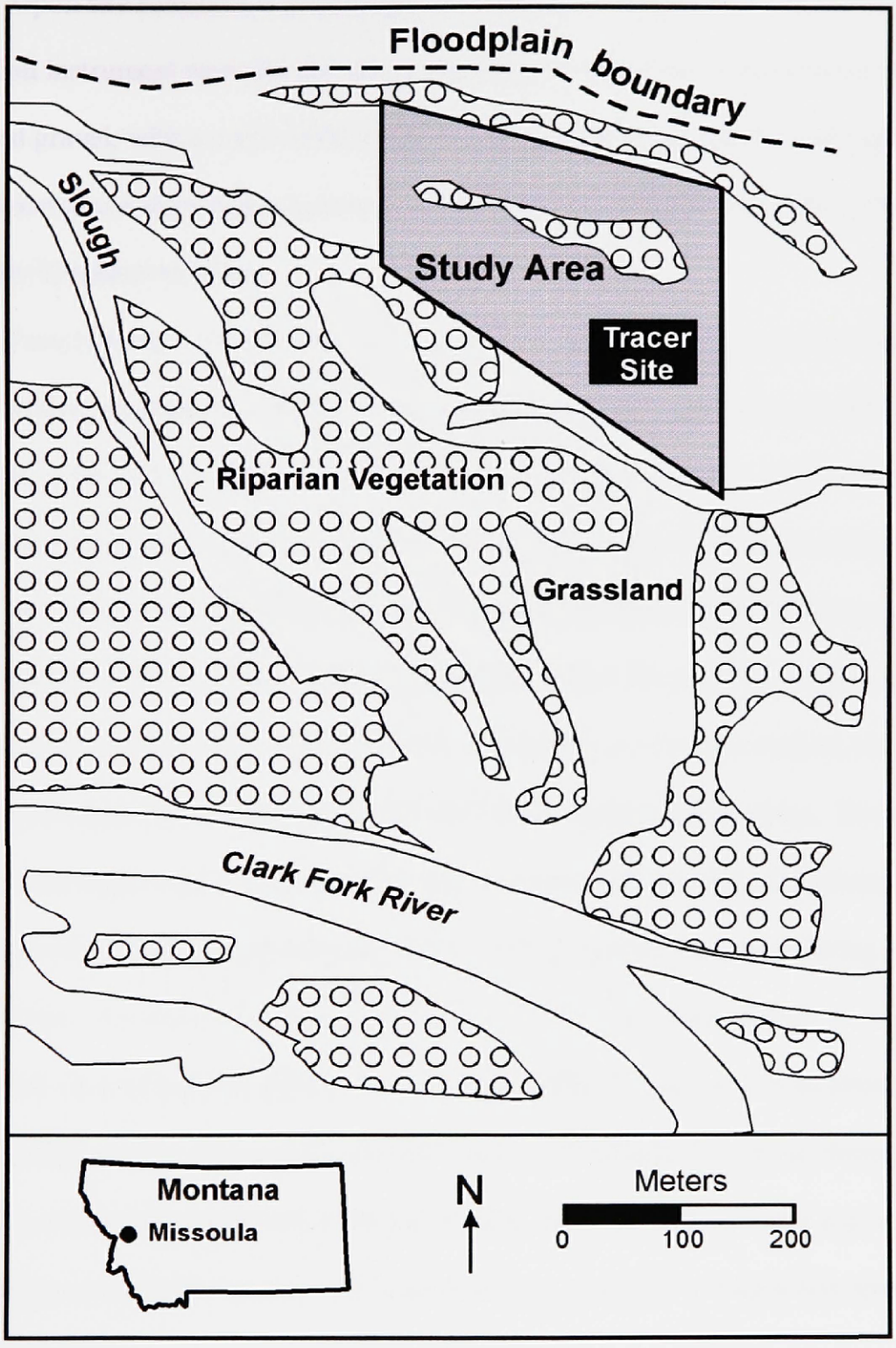


Figure 2. Erskine Fishing Access, Missoula County, Montana.

Upon site selection, a preliminary investigation with the SeisSmart S12 seismic refraction instrument revealed the site is underlain by what was interpreted to be coarse sand and gravel, with a water table at approximately 6 to 9 feet below land surface. Permission to use the site was granted by Montana Fish Wildlife and Parks (MFWP).

3.2 Site Characterization

Establishing a suitable test site required installing an extensive observation and injection-well network to evaluate the stratigraphy and hydrogeologic properties of the area, and to provide an optimal test field for the tracer experiments. Initially, five boreholes were drilled, with total depths 18 to 21 feet, using a 7 3/4-inch hollow-stem auger. Wells were completed as 2-inch diameter polyvinyl chloride (PVC) monitoring wells, with the bottom 1.7 feet of the casing fitted with a 20 slot PVC screen, and designated as EE-2 to EE-6. One 50-foot borehole (EE-1) was also drilled, and samples taken from augured cuttings with a 2 1/2 -inch O.D., split-spoon sampler. Each of the EE borings was logged and site stratigraphy was interpreted by constructing cross sections. Grain size distributions were described from sieving samples collected during well construction. All wells were developed by surge block and hand bailing.

An electromagnetic (EM) survey, with the EM-31, was used in an attempt to further define aquifer stratigraphy and structure. An EM grid was set up throughout the field site, running transects with 3 feet by 10 feet spacing. Subsequently a ground penetrating radar (GPR) system was used to collect 23 profiles using 6 feet spacing (Magruder 1998).

Actual depth to groundwater and general direction of groundwater flow was determined from the initial 2-inch diameter wells. These data were used for subsequent

installation of additional monitoring-wells designed to further characterize the hydrogeological properties of the aquifer. Figure 3 illustrates the well designs and site instrumentation in relation to the ground surface and water table. Several smaller piezometers, consisting of 1/2 to 3/4-inch diameter galvanized steel and PVC pipes were placed at a depth of 12 feet (Wells labeled "P" in Figure 3). Holes were drilled in the bottom 1.5 feet of the PVC pipes, and covered with a fine nylon mesh screen, whereas the galvanized pipe was unperforated. Using a jackhammer, the steel pipes were driven into the ground, with a carriage bolt inserted into the end to protect the base. Where possible, a PVC piezometer was inserted and the steel pipe removed. Also, 3-foot long sandpoints (SP), placed on 6 feet of 1 $^{1}/_{4}$-inch diameter steel pipe, were driven to a depth of approximately 9 feet with a Geoprobe. Additional sandpoints were located upgradient of the monitoring well network and used as injection wells I-1 to I-5. These wells were spaced 10 feet apart. Two staff gauges, S1 and S2, were installed in a low-lying slough to the west of the field. All wells were surveyed with a total survey station to establish their locations and elevations (Figure 4).

A Stevens Type F continuous water level recorder was set up at well EE-6 to record water levels. In the other wells, water levels were initially measured weekly using an electric tape, then monthly after the tracer tests commenced. Temperature, conductivity, pH, dissolved oxygen, along with general, gross ionic water chemistry, were measured at selected locations, using standard procedures to characterize the groundwater geochemistry.

3.3 Aquifer Tests

Standard, constant discharge aquifer tests were performed in an attempt to

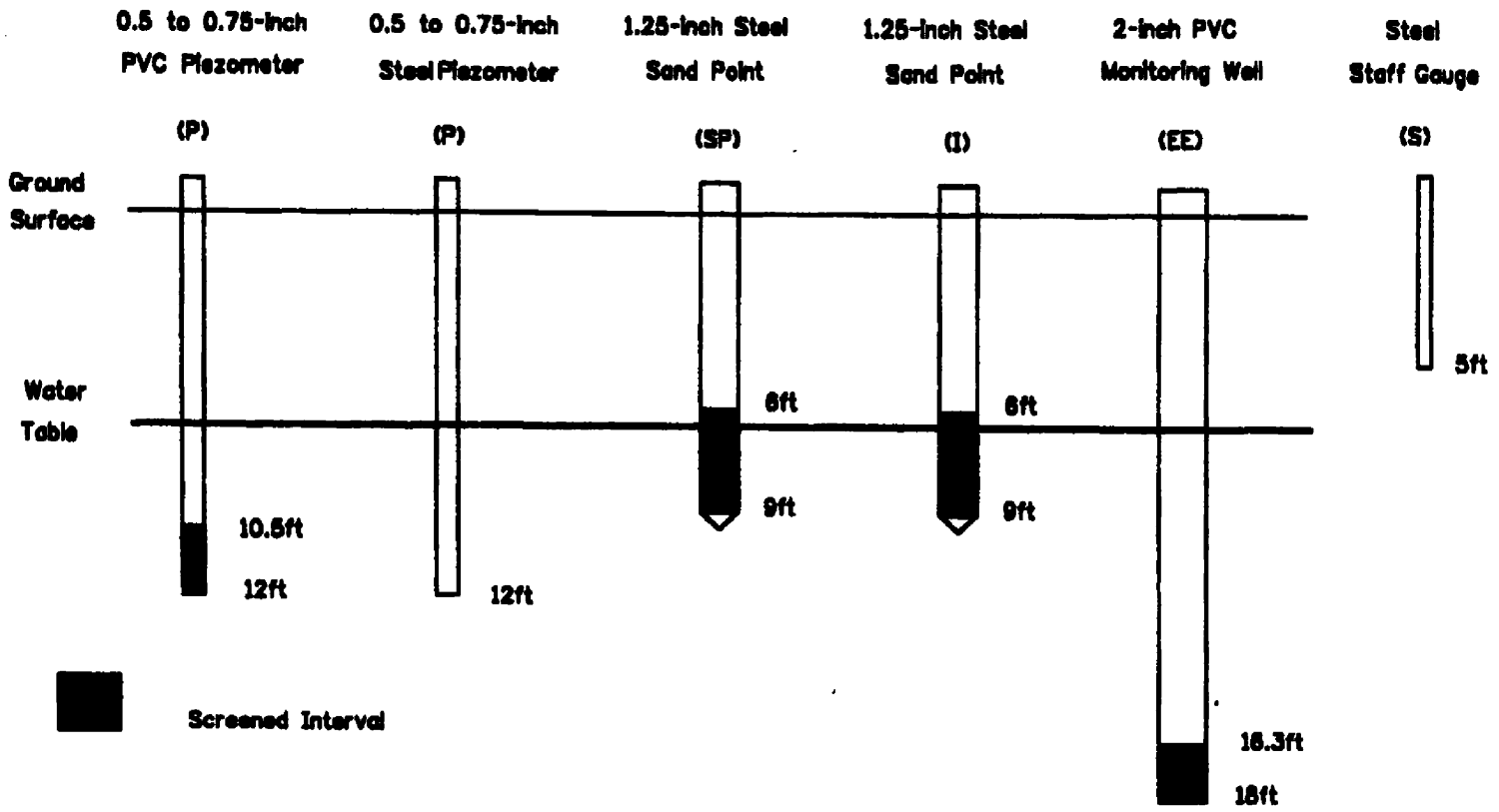


Figure 3. Site instrumentation design.

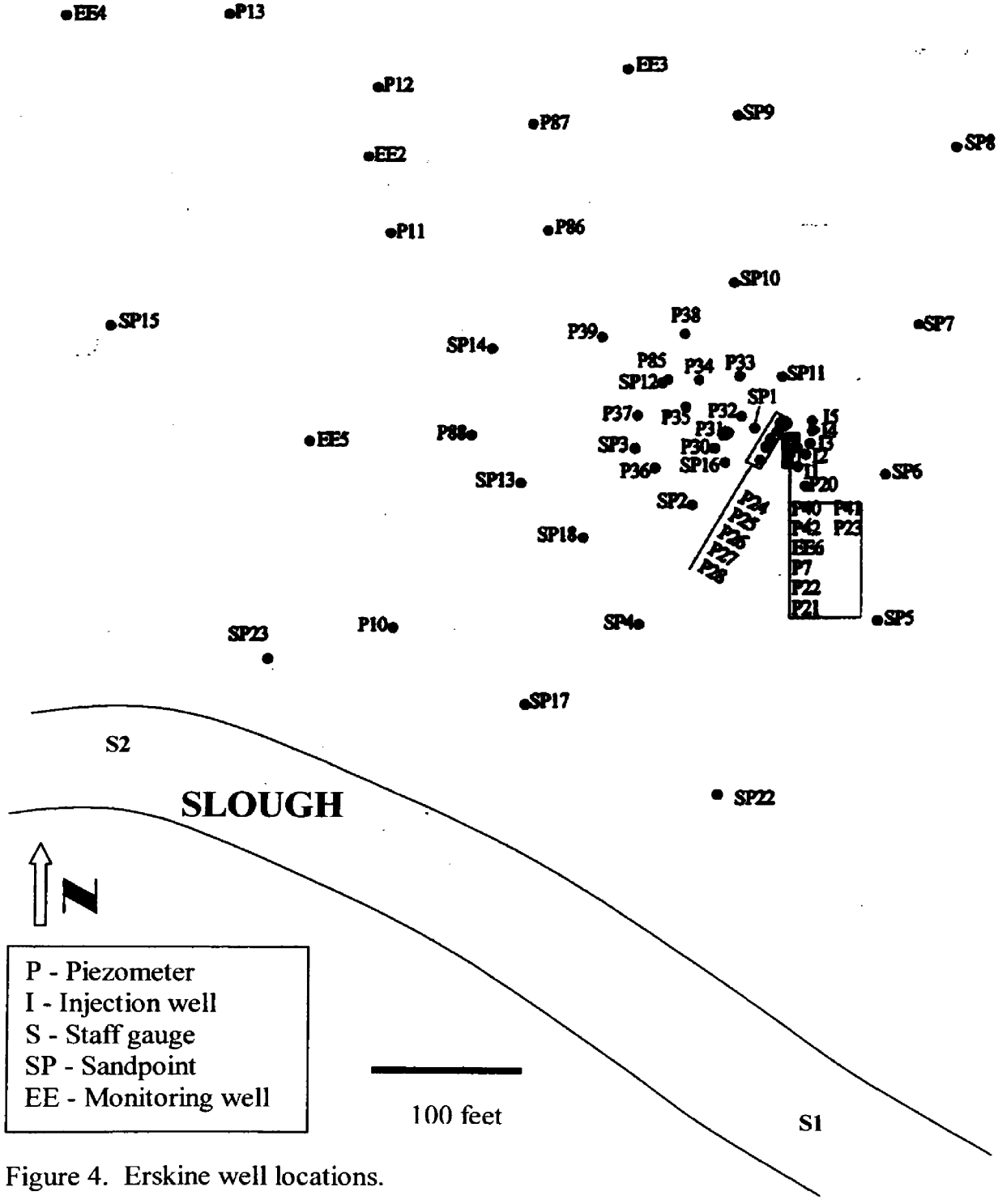


Figure 4. Erskine well locations.

characterize the magnitude and distribution of aquifer properties. A pumping test run at a constant rate of 30 gpm was performed, with flow rates measured using a stopwatch and volume increments marked on a plastic barrel. Additional aquifer testing performed by Kiley (1997) used a production well pumping at 98 gpm and seven observation wells.

Six slug tests, using an SE 1000C Environmental Logger, at wells EE-5 and EE-6 established preliminary hydraulic conductivity values at the site.

3.4 Conservative Tracer Tests

Two rhodamine WT dye and three sodium bromide tracer tests were conducted to establish general groundwater flowpaths and travel times. Tracers were injected as a single slug for each test. Various tracer concentrations were used, along with different injection wells and sampling intervals, in order to develop an optimal tracer experiment (Table 1). All samples were obtained using a portable peristaltic pump, collected in clean, 50 ml high-density polyethylene (HDPE) bottles, and placed into a cooler for transport to the lab. Sodium bromide samples were filtered in the field and analyzed with an ion chromatograph (IC) using standard procedures at the Murdoch Environmental lab at the University of Montana Department of Geology. The analytical detection limits were 0.1 mg/l for the bromide natural gradient experiments (DeBorde et al 1999). A fluorometer was calibrated and used to evaluate the rhodamine WT dye samples.

3.5 Virus Transport

One natural gradient MS-2 bacteriophage tracer test was conducted, in preparation for future multiple virus experiments at the site (Woessner and DeBorde 1998, DeBorde et al 1999). MS-2 was seeded into injection well I-4 as a single slug, following the third bromide test. Groundwater from a background well was used to

Table 1. Tracer test summary.

Test Date	Injection Well	Compound	Concentration	Sampling Interval (hr)	Total Test Time (hr)
12/15/95	I-3	Rhodamine WT	25 ml in 19L dionized water	16-28	334
12/27/95	I-3	Bromide	6000 mg/L	4-6	70
3/15/96	I-5	Rhodamine WT	75 ml in 19L dionized water	6-12	48
3/15/96	I-4	Bromide	3900 mg/L	6-12	42
3/25/96	I-4	Bromide	6000 mg/L	1-11	40

dilute the bacteriophage tracer to a concentration of $1x10^{12}$ PFU (Plaque Forming Units)/ml. Flexible, polyethylene tubing was dedicated to each observation well during the MS-2 sampling phase. Samples were collected in sterile 50ml polypropylene vials using a portable peristaltic pump at 2-hour intervals. Latex gloves were worn and changed for each well sampled, to guard against cross contamination. Samples were immediately placed into coolers and transported on ice to the lab for analysis. Assays performed were in accordance with the USEPA Manual of Methods for Virology (USEPA 1984). The virus analyses for MS-2 experiments were determined using appropriate host bacteria in single layer agar, with plaquing assays having a detection limit of 0.1 PFU/ml (DeBorde et al 1998).

4.0 Results

4.1 Site Characterization

The land surface is generally level. A thin layer of soil and silt overlays medium gravelly sand and sandy gravel, grading down to moderately well sorted, rounded gravel. This sequence, which contains very little interbedded clay or silt, is characteristic of a fining upwards fluvial deposit (Figures 5 and 6). Grain-size analyses (Table 2) show a uniformity coefficient (Cu) range of 2-42, with most of the sediments poorly sorted.

The EM survey (Figure 7) showed patterns of high and low conductivity, though no correlation with the apparent flow field or stratigraphy. The lack of a clear correlation was perhaps due to the presence of existing steel wells or the depth-integrating nature of the tool.

Ground penetrating radar revealed the presence of subsurface stratigraphy that

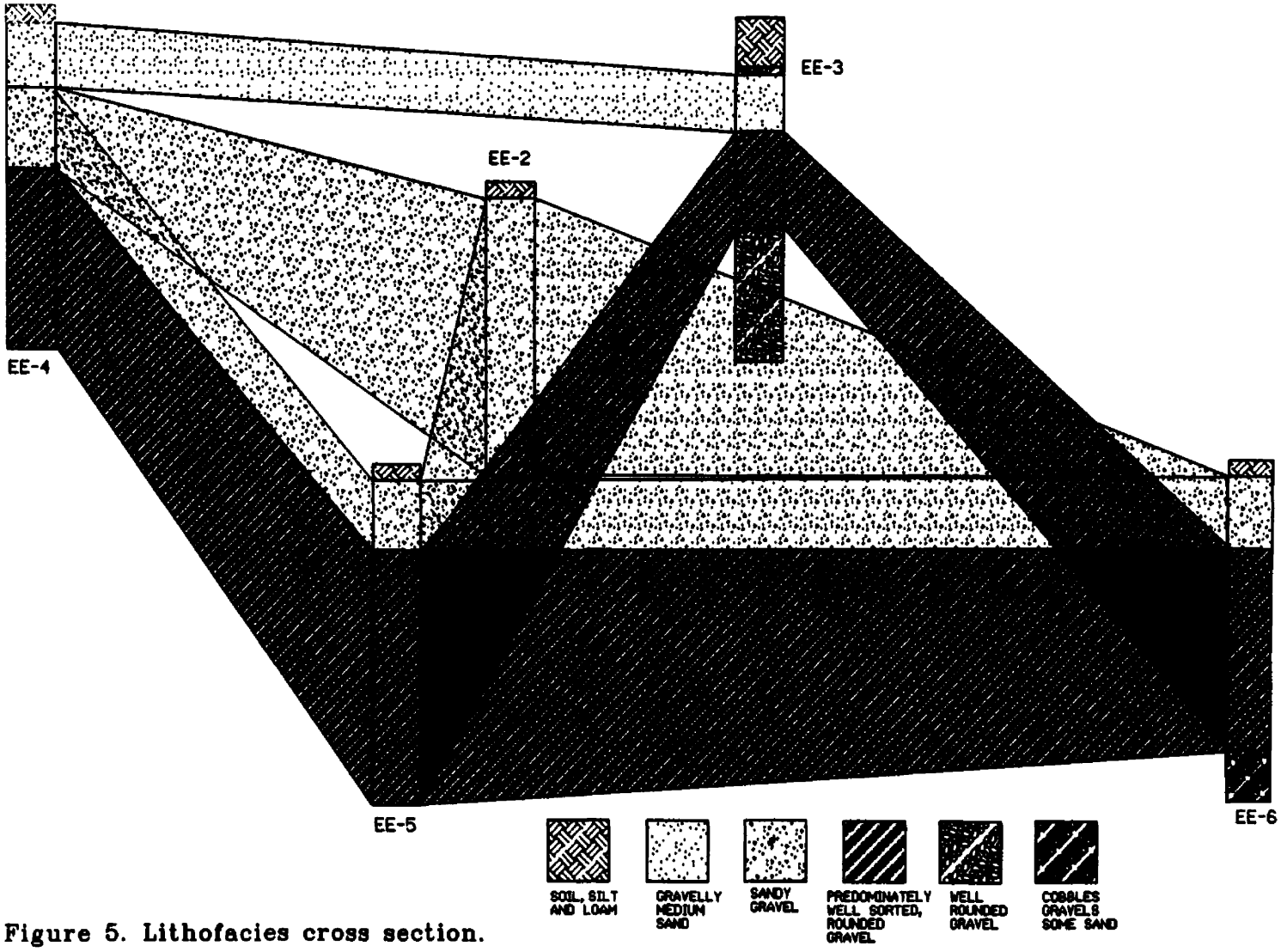


Figure 5. Lithofacies cross section.

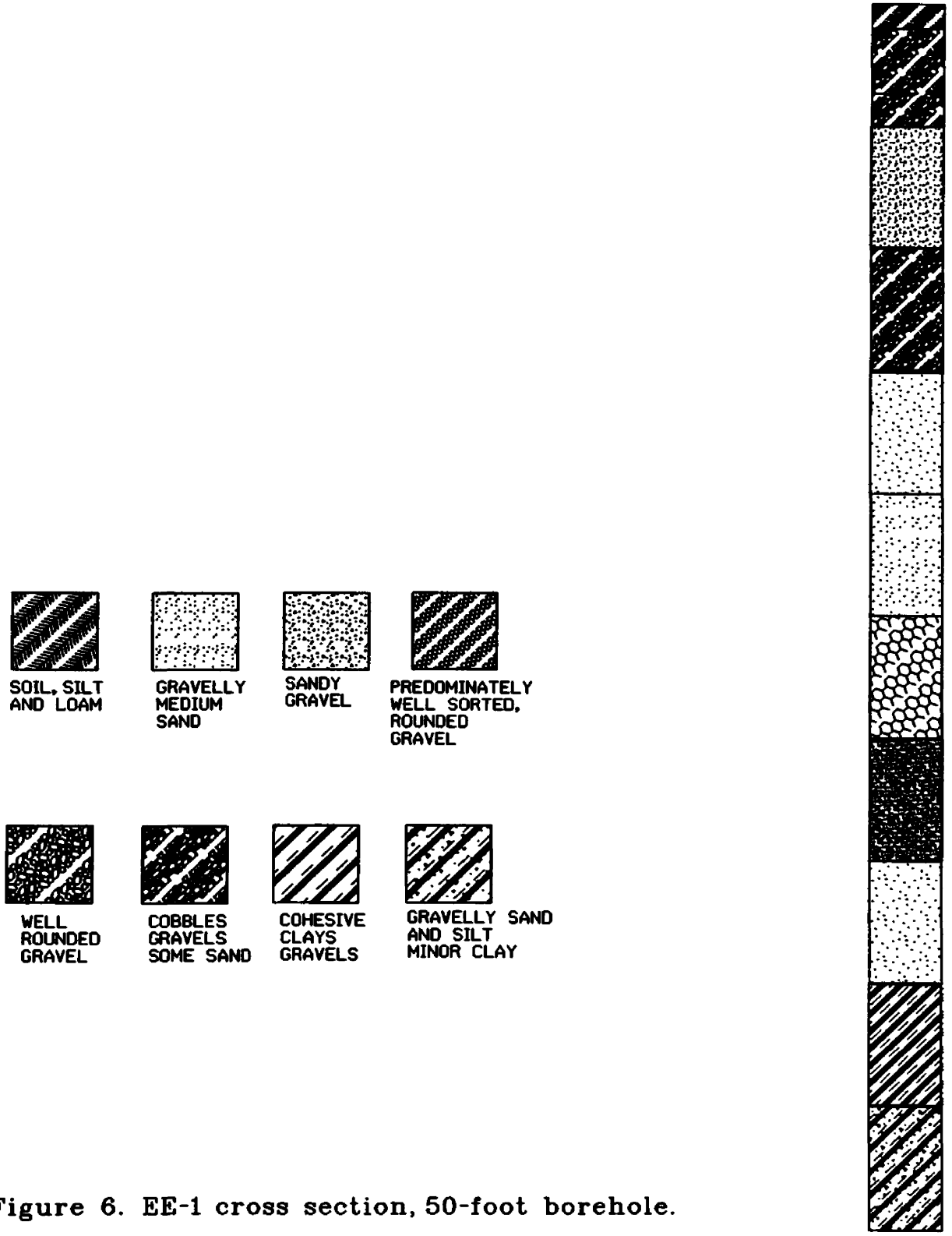


Figure 6. EE-1 cross section, 50-foot borehole.

Table 2. Erskine grain size analysis summary.

	EE-1 5'	EE-1 10'	EE-1 15'	EE-2 18'	EE-3 21'	EE-4 21'	EE-5 21'	EE-6 21'
grain size	wt. grams	wt. grams	wt. grams	wt. grams	wt. grams	wt. grams	wt. grams	wt. grams
<63u	2.92	11.74	10.99	5.22	9.37	10.49	4.9	9.03
63u	2.5	17.59	13.81	5.01	12.3	18.84	10.6	25.6
125u	4.54	37.09	26.02	13.88	18.91	56.08	21.22	69.22
250u	24.56	270.17	336.65	128.59	279.79	356.02	329.01	550.86
500u	26.72	512.74	45.96	210.03	285.72	317.41	239.36	111.31
1mm	23.48	112.74	11.45	40.88	39.47	129.73	80	121.04
2mm	29.97	184.39	7.9	61.1	51.53	194.02	148.12	196.3
4mm	88.71	325.8	0.17	129.38	86.29	394.87	311.22	397.65
8mm	392.65	447.36		425.19	424.05	1192.14	872.7	1198.21
25mm	198.83	62.85		36.33	259.13	333.6	23.58	341.33
38mm					161.34	110.66	365.92	
TOTAL	794.88	1982.47	452.95	1055.61	1627.9	3113.86	2406.63	3020.55
d60	18	4.5	0.39	9	15	13	13	12
d10	1.8	0.38	0.25	0.4	0.36	0.4	0.4	0.33
Cu	10	12	2	23	42	33	33	36

	Mean	Range
d60	11	3.9 - 18
d10	0.82	0.33 - 2.5
Cu	24	2 - 42

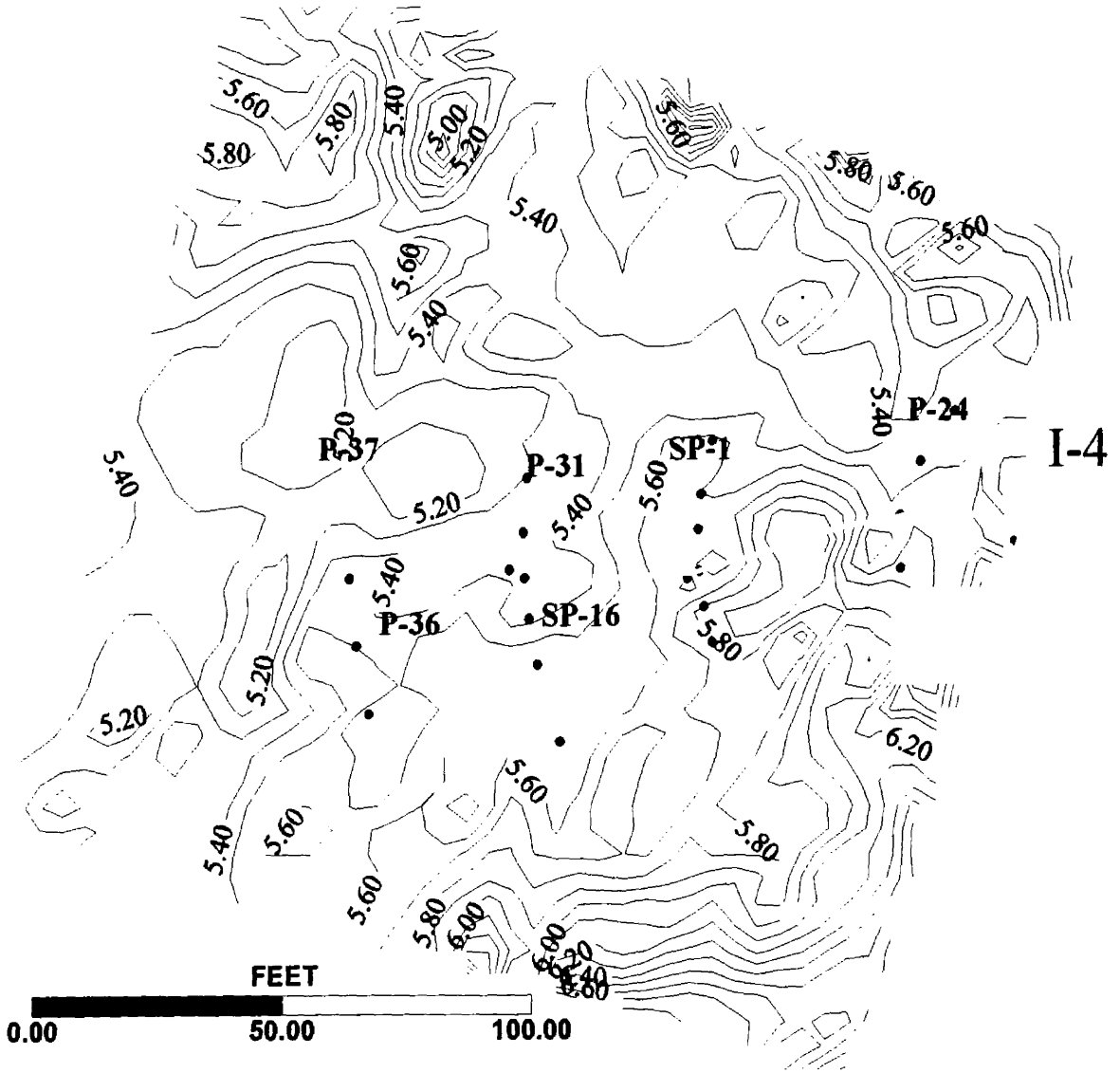


Figure 7. EM survey specific conductance map, arrow indicates groundwater flowpath (measurements in umhos).

was interpreted as a lateral accretion point bar, deposited by a fluvial system (Figures 8-10). Magruder (1998) also observed offlapping, inclined epsilon crossbedding, downlapping and erosional truncation of bedding, along with horizontally layered slough fill in the point bar deposit. This channel point bar appears to have migrated towards the north - northwest, with alternating fine and coarse grain deposits that may correlate with the preferential groundwater flowpaths. However, the use of GPR at the site could not define specific types of grainsizes and sorting that cause localized high K, and showed the water table as a saturation gradient instead of a distinct interface.

4.2 Groundwater Flow and Aquifer Hydrologic Properties

Erskine Fishing Access lies in the floodplain, resulting in a shallow water table under the influence of the nearby Clark Fork River. The aquifer is unconfined, containing 14 feet of saturated sand and gravel underlain by a sequence of sand. The water table ranges from 2.2 to 7 ft below land surface as shown in the hydrograph in Figure 11. Groundwater flows generally from the east to a northwesterly direction, and the site has a hydraulic gradient of .0005, as interpolated from potentiometric maps (Figure 12). The extremely low gradient made standard head mapping and interpretation of precise groundwater flow direction difficult in the area.

Based on permeameter experiments, Clark (1986) estimated a porosity value of 19.7% for the Clark Fork River floodplain. In situ measurements of physical and chemical properties are presented in Tables 3 and 4.

Slug tests revealed hydraulic conductivities ranging from 1,400 to 2,500 ft/day, with an average K of about 1,900 ft/day (Table 5). Aquifer pumping tests did not

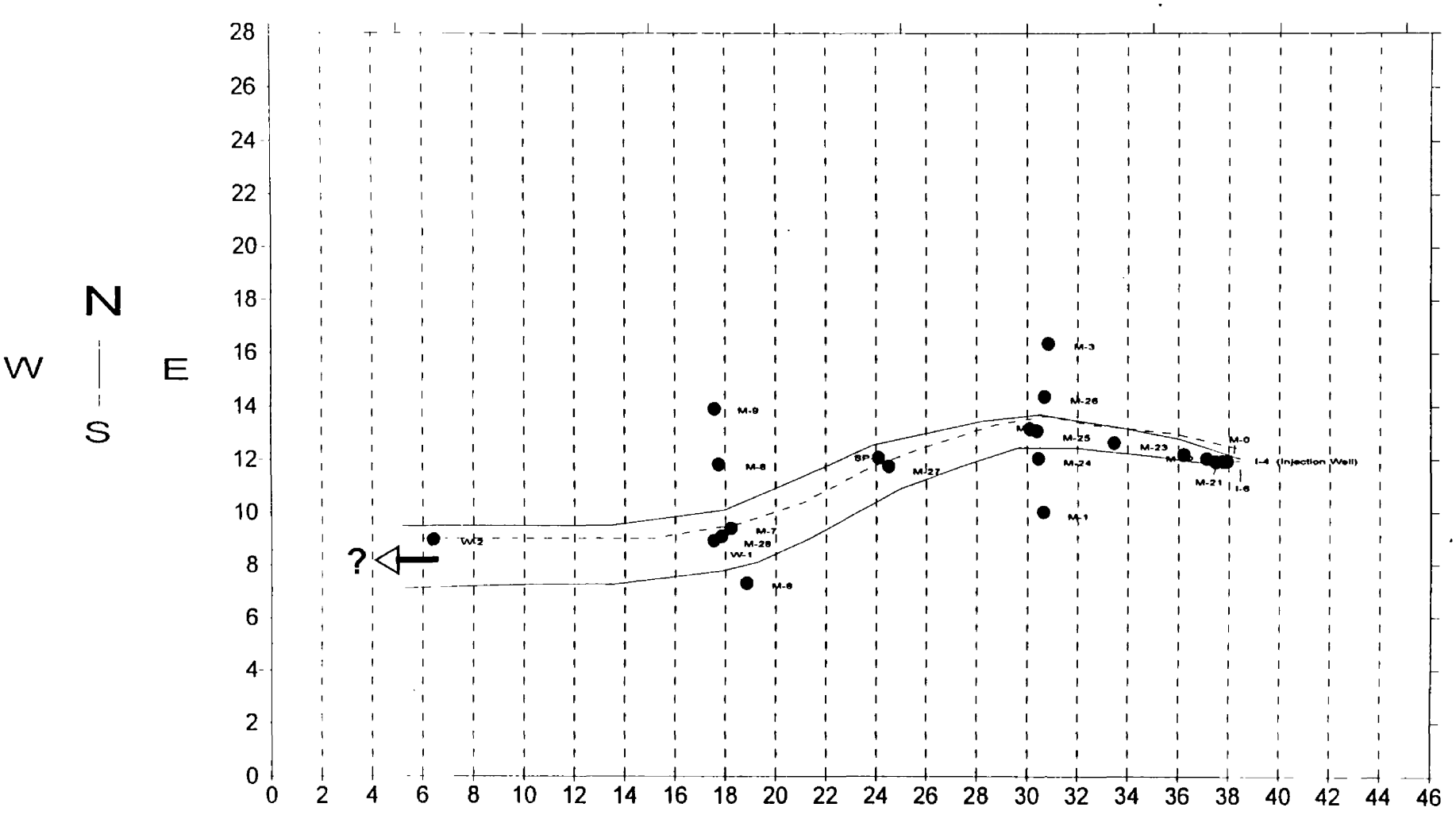


Figure 8. Ground penetrating radar transects, distances in meters (Magruder 1998).

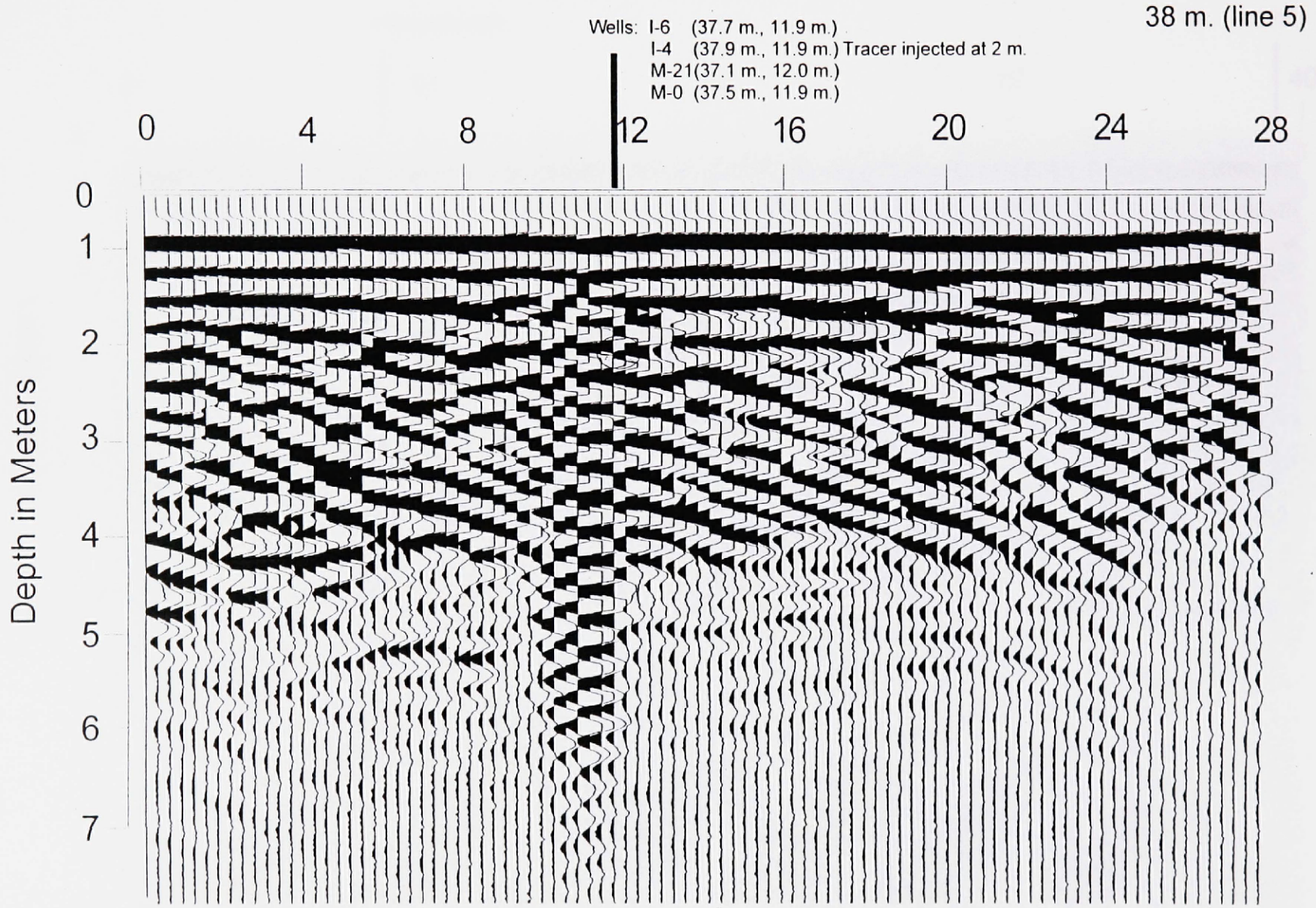


Figure 9. GPR profile through injection well I-4 at transect 38 (Magruder 1998).

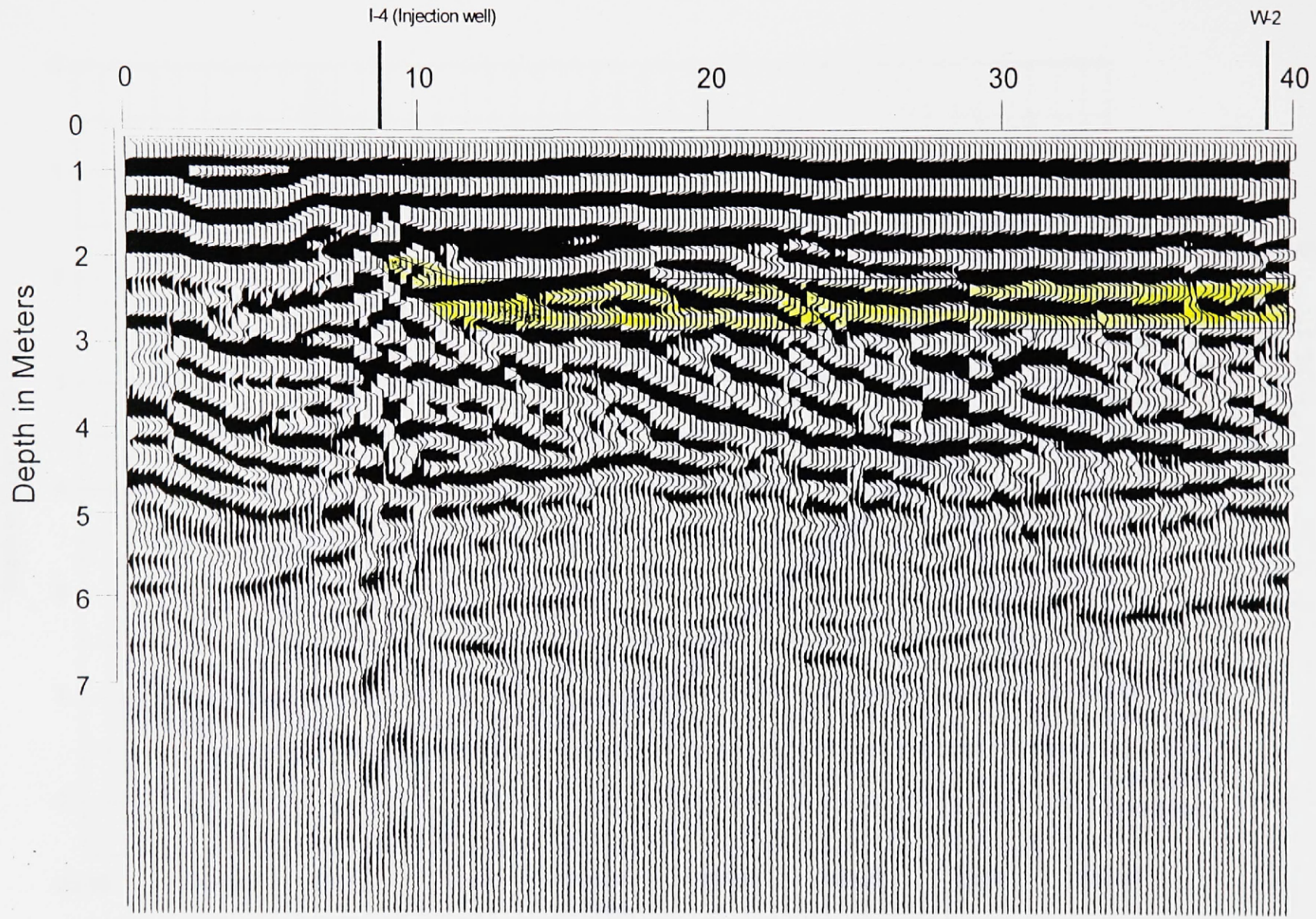


Figure 10. GPR profile I-4 to W-2 running East-West. Yellow indicates tracer path (Magruder 1998).

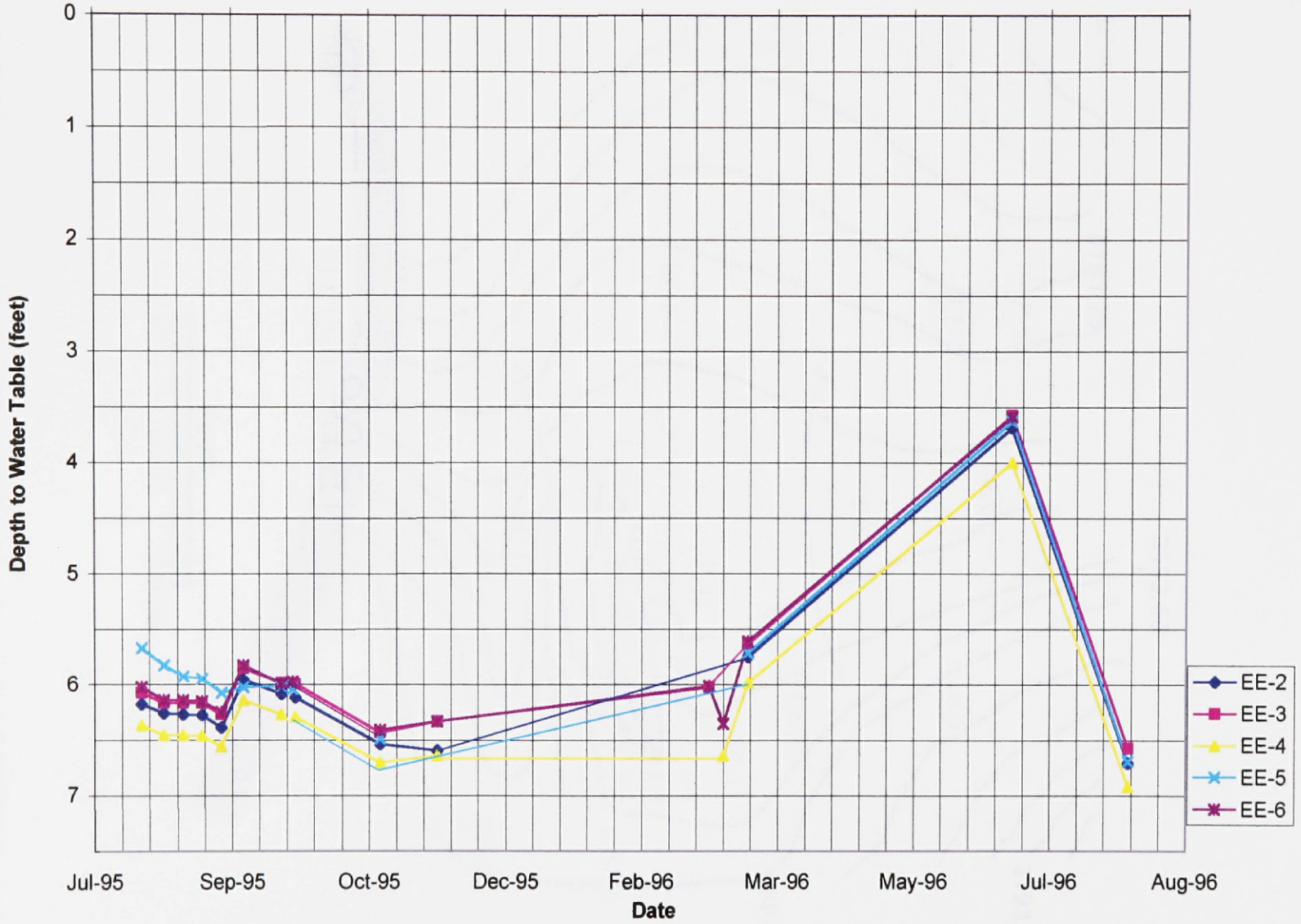


Figure 11. Hydrograph of water table fluctuations, August 1995 to August 1996.

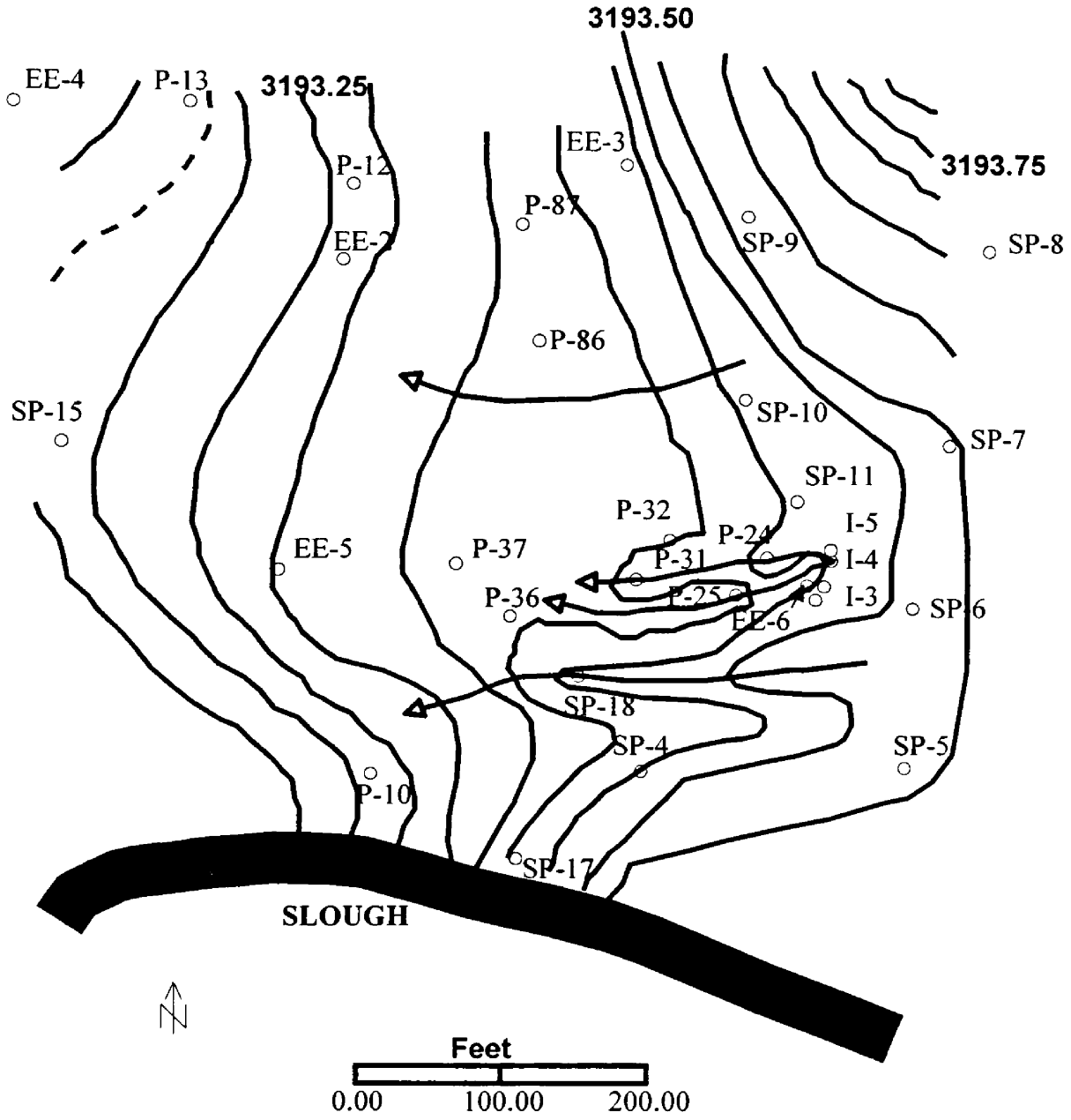


Figure 12. Erskine potentiometric map using .05 ft contour intervals and 3200 ft datum.

Table 3. In situ groundwater properties for wells EE-2 and P-20.

Well #	Conductivity (umhos)	Temperature (C)	pH	Dissolved Oxygen (mg/L)
EE-2	278	10.2	7.21	3.50
P-20	298	10.4	7.19	3.40
Average	288	10.3	7.20	3.45

Table 4. Water chemistry summary.

Parameter	Concentration (mg/l)
Ca	53.7
Fe	0.01
K	2.3
Mg	16.9
Na	8.6
Cl	7.3
NO3	0.7
SO4	16.3
HCO3	249
C (organic)	2.1
C (inorganic)	49

Table 5. Erskine slug test results, using Hvorslev (1951).

Well #	Hydraulic Cond. (ft/day)	EE-5 Average K	EE-6 Average K	Site Average K
EE-5a	1500	1600 ft/day	2100 ft/day	1900 ft/day
EE-5b	1600			
EE-5c	1800			
EE-6a	2500			
EE-6b	2300			
EE-6c	1400			

produce drawdown in adjacent wells, as illustrated in Table 6. Pumping at 30 gpm was insufficient to evaluate the extremely highly conductive aquifer. However, pumping at 98 gpm produced sufficient drawdown in observation wells to allow interpretation of hydraulic conductivities Kiley (1997).

Site hydraulic conductivity values derived from slug, pumping and tracer tests were log transformed ($\log_{10}$) and plotted in Figure 13. The distribution mean is 3.90, with a standard deviation 0.62, and variance of 0.38. These distribution data suggest the hydraulic properties within the tracer site are quite heterogeneous.

4.3 Tracer Test Analyses

Rhodamine WT and sodium bromide tracer tests were used to examine aquifer properties and to design a more complex virus transport experiment.

The initial natural gradient tests using injection well I-3 indicated a western groundwater flowpath (Figure 14). The rhodamine WT dye was detected 60 feet from the injection point within 44 hours of the initiation of the test (Figure 15), though the rapid movement of the dye precluded exact identification of a breakthrough curve. A more frequent sampling interval was implemented in the bromide tracer test, allowing for a more accurate capture of the breakthrough data (Figure 16). Velocity estimates ranged from 20 to 42 ft/d.

The second rhodamine WT test on 3/15/96, using injection well I-5, resulted in no detection of the tracer in any of the wells sampled, indicating some type of boundary between I-5 and the rest of the flowfield.

Subsequent bromide tracer tests using injection well I-4 further defined the flowpath (Figure 17) and groundwater velocities. These analyses indicated groundwater

Table 6. Time-drawdown data from EE-6 pumping test @30 gpm.

Well #	Water Levels						
	t = 0	t = 5	t = 10	t = 15	t = 25	t = 45	t = 60
EE-6	7.17						
P-22	7.51	7.51	7.51	7.51	7.53	7.52	7.52
P-23	8.07	8.07	8.07	8.06	8.07	8.07	8.07
P-40	7.94	7.94	7.94	7.95	7.96	7.95	7.94

All measurements in feet
t = time in minutes since pumping began

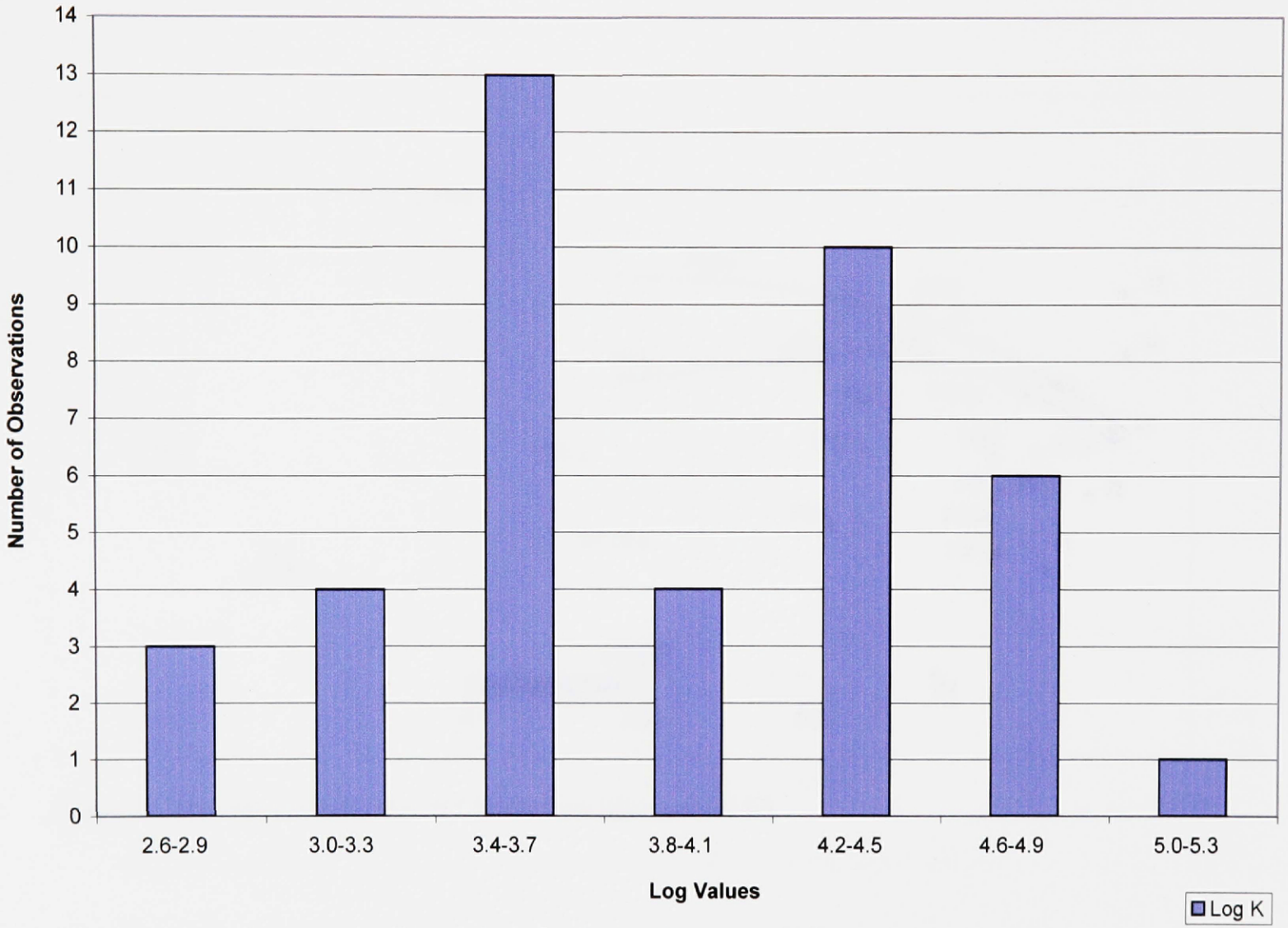


Figure 13. Frequency of log values for hydraulic conductivity.

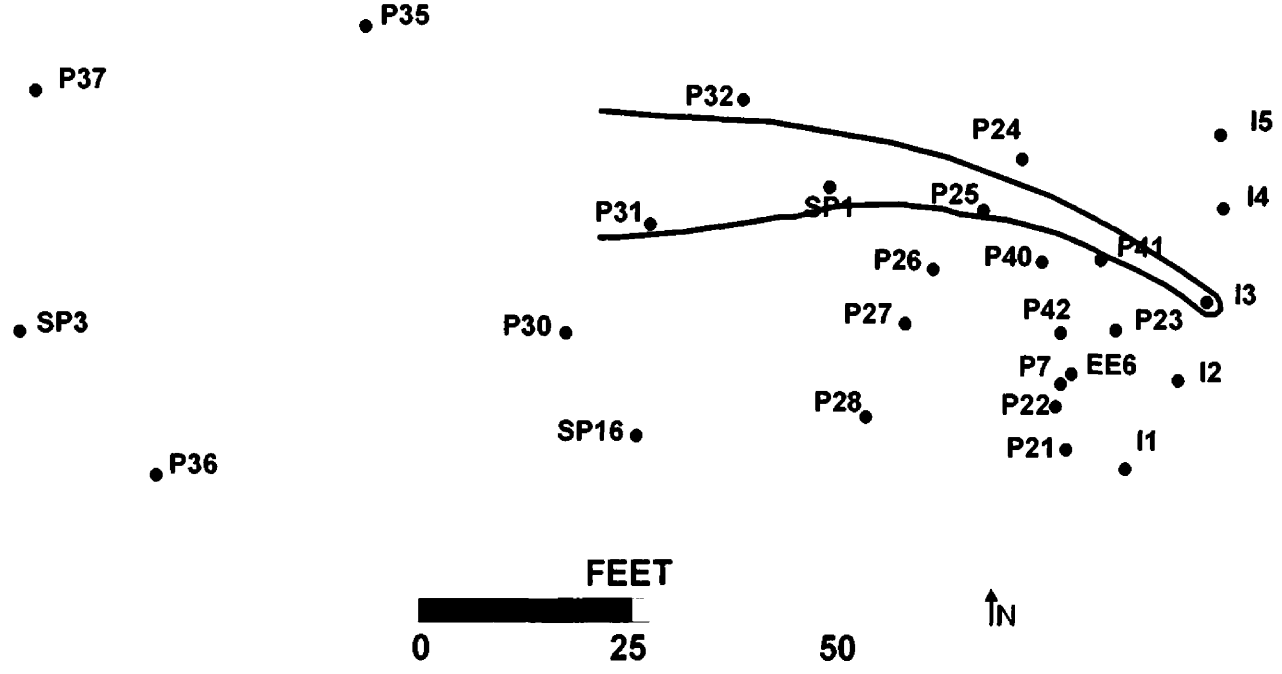


Figure 14. Bromide and rhodamine WT plume from injection well I-3.

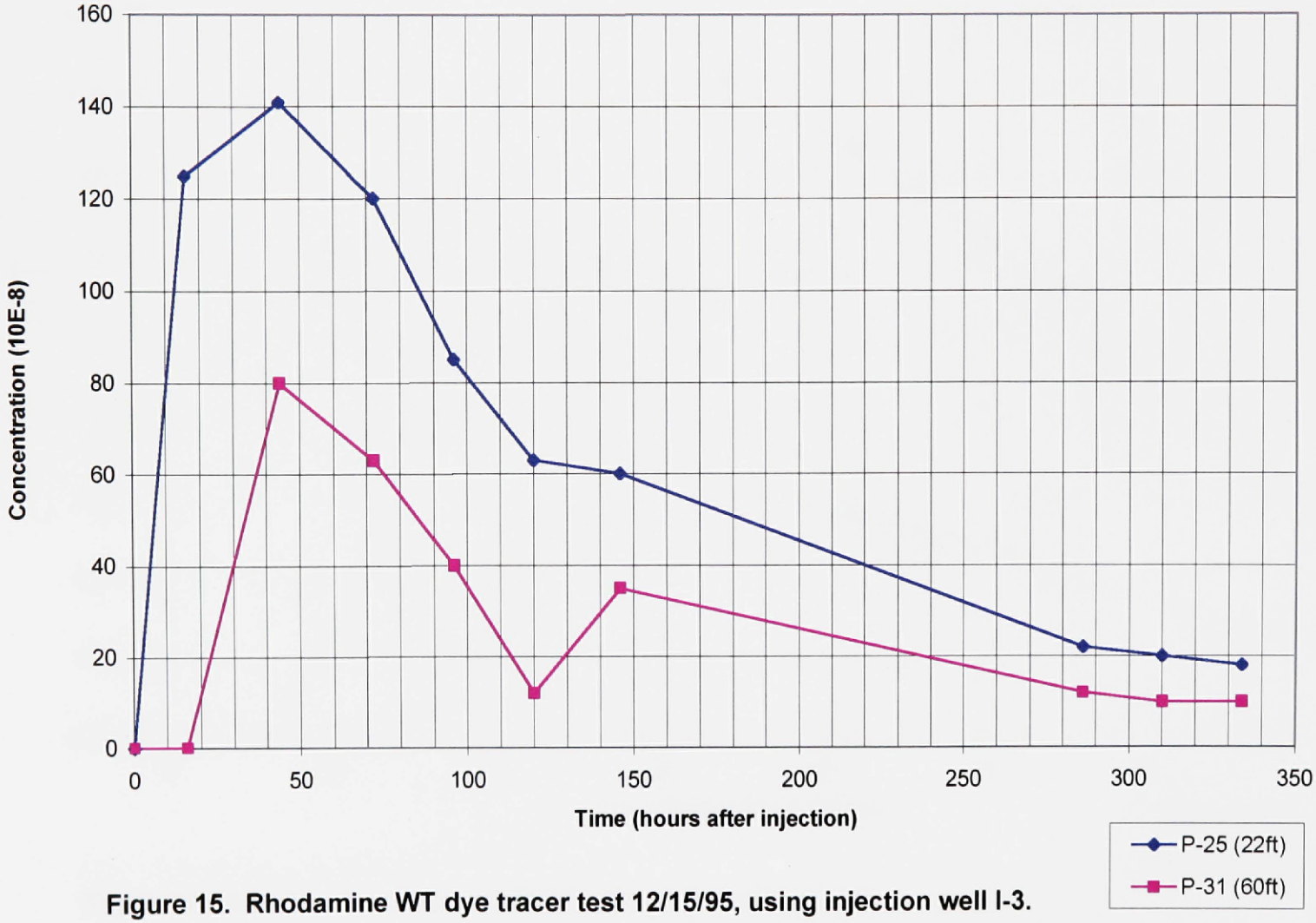


Figure 15. Rhodamine WT dye tracer test 12/15/95, using injection well I-3.

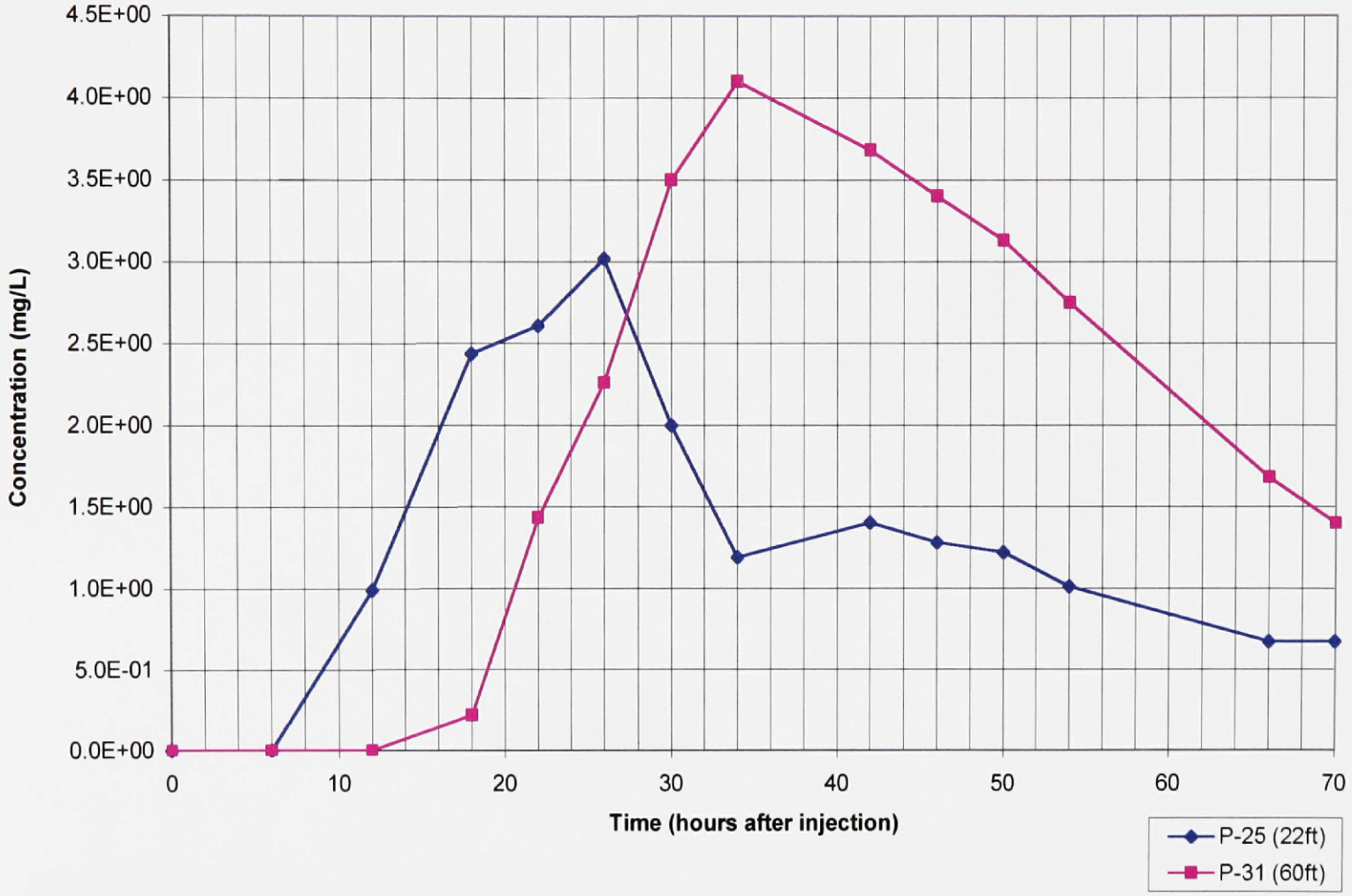


Figure 16. Bromide tracer test 12/27/95, using injection well I-3.

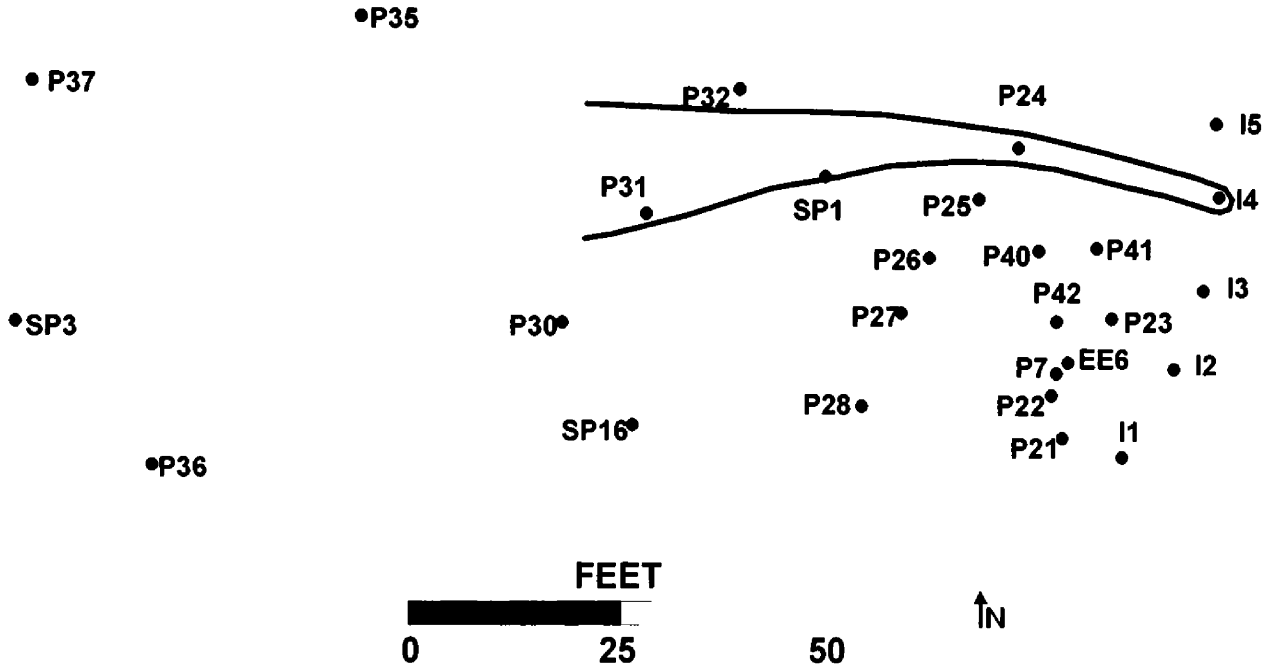


Figure 17. Bromide plume from injection well I-4.

velocities varying between 31 and 92 ft/d (Figures 18 and 19) and defined a west to northwest groundwater flowpath.

Assuming a hydraulic gradient of 0.0005 and a porosity of 0.2, Table 7 presents computed K values based on bromide tracer test velocity measurements.

Table 8 summarizes dynamic dispersivity values calculated from tracer experiments at P-24 and P-31. The high Peclet numbers, ranging from 7 to 100, indicate mechanical dispersion controls the mass transport with little effects from diffusion. The longitudinal dispersivity values averaged 1.3 feet; transverse values were estimated as one-tenth of the longitudinal value.

4.4 Virus Transport

The coliphage MS-2 was seeded by gravity into injection well I-4 over a 5-minute period, after establishing appropriate sampling intervals with the bromide tracer test results. Figures 20 and 21 show breakthrough curves for the closest wells, P-24 and P-25 located 23 feet and 27 feet, respectfully, from I-4. The first peaks arrived within 10 hours after injection. Although the wells are only eight feet apart laterally, the concentrations differ by five orders of magnitude. Breakthrough curves are illustrated in Figures 22 - 24 for the next set of wells (P-32, P-31 and P-30), ranging from 55 to 77 feet from injection well I-4. Concentrations peaked between 14 and 22 hours. Analyses for P-35, P-36 and P-37, wells located 99 ft, 124 ft and 134 feet away from I-4 show higher concentrations at P-37, the farthest from the point of injection (Figure 25). The MS-2 plume in Figure 26 plotted 36 hours after injection reveals the apparent central area of the plume encompassing wells P-24 and P-31.

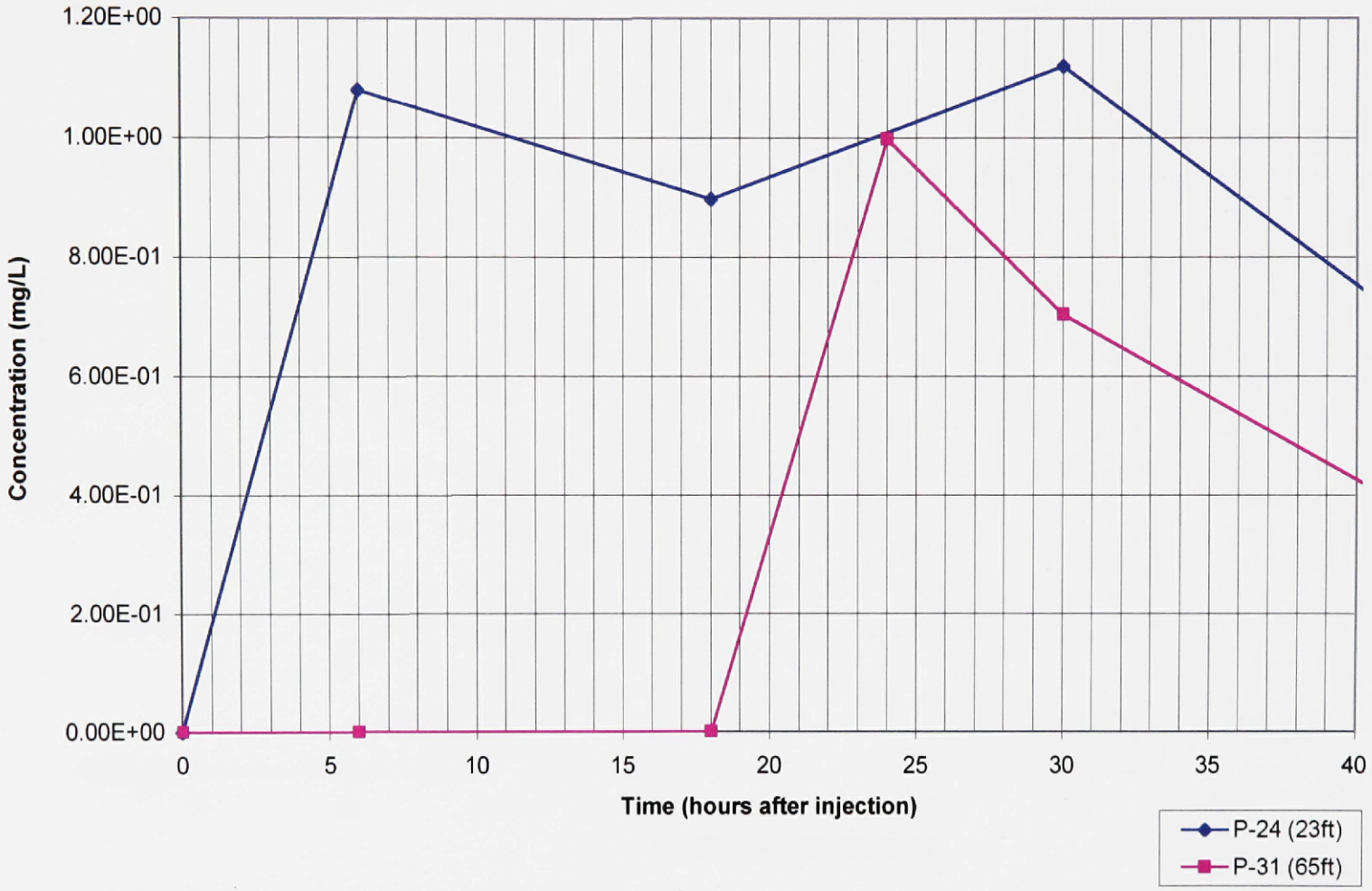


Figure 18. Bromide tracer test 3/15/96, using injection well I-4.

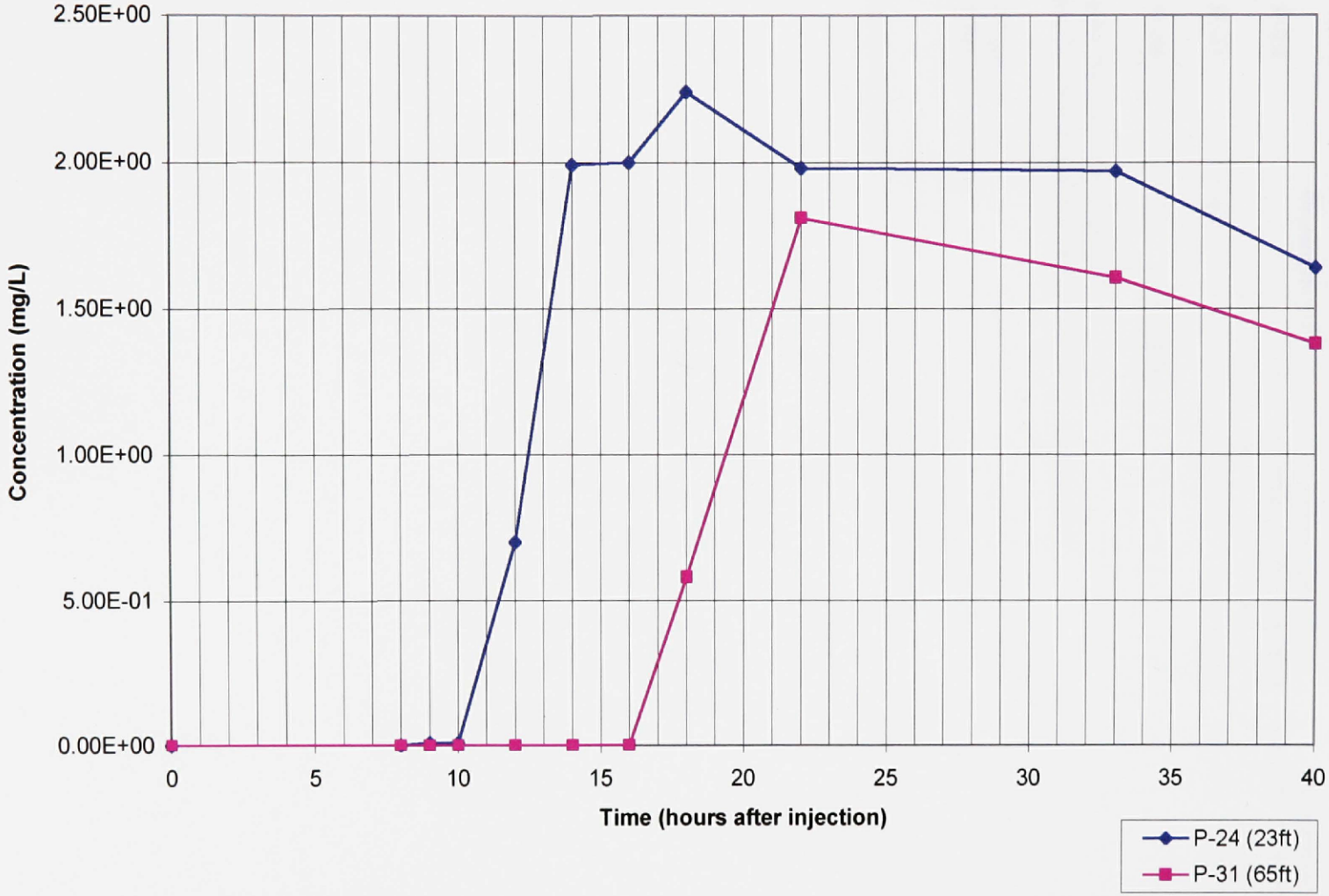


Figure 19. Bromide tracer test 3/25/96, using injection well I-4.

Table 7. Hydraulic conductivity values based on velocity measurements.

Well #	Tracer Test					
	Bromide I-3		Bromide I-4		Bromide I-4	
P-24			v = 92	K = 36800	v = 31	K = 12300
P-31	v = 42	K = 17000	v = 65	K = 26000	v = 71	K = 28400
P-25	v = 20	K = 8000				

Velocity range = 20 - 92 ft/d
Hydraulic conductivity range = 8,000 - 36,800 ft/d

Average v = 54
Average K = 21000

All values in ft/day

Table 8. Dispersivity summary for wells P-24 and P-31 using Sauty type curves (1980).

Bromide Tracer 3/15/96

P-24		P-31	
Pe =	7	Pe =	20
DL =	59.14	DL =	20.7
	59		20
L dispersivity=	3.21 ft	L dispersivity=	0.31 ft
T dispersivity=	0.32 ft	T dispersivity=	0.03 ft

Bromide Tracer 3/25/96

P-24		P-31	
Pe =	25	Pe =	100
DL =	16.6	DL =	14.3
	16.6		14.3
L dispersivity=	0.54 ft	L dispersivity=	0.20 ft
T dispersivity=	0.05 ft	T dispersivity=	0.02 ft

MS-2 Bacteriophage tracer test.

P-24		P-31	
Pe =	25	Pe =	28
DL =	23.1	DL =	233.4
	23.1		233
L dispersivity=	0.92 ft	L dispersivity=	2.35 ft
T dispersivity=	0.09 ft	T dispersivity=	0.24 ft

Range

L dispersivity= 0.2 to 3.21 ft
T dispersivity = 0.02 to 0.32 ft
Pe = 7 to 100

Average

L dispersivity= 1.3 ft
T dispersivity = 0.13 ft

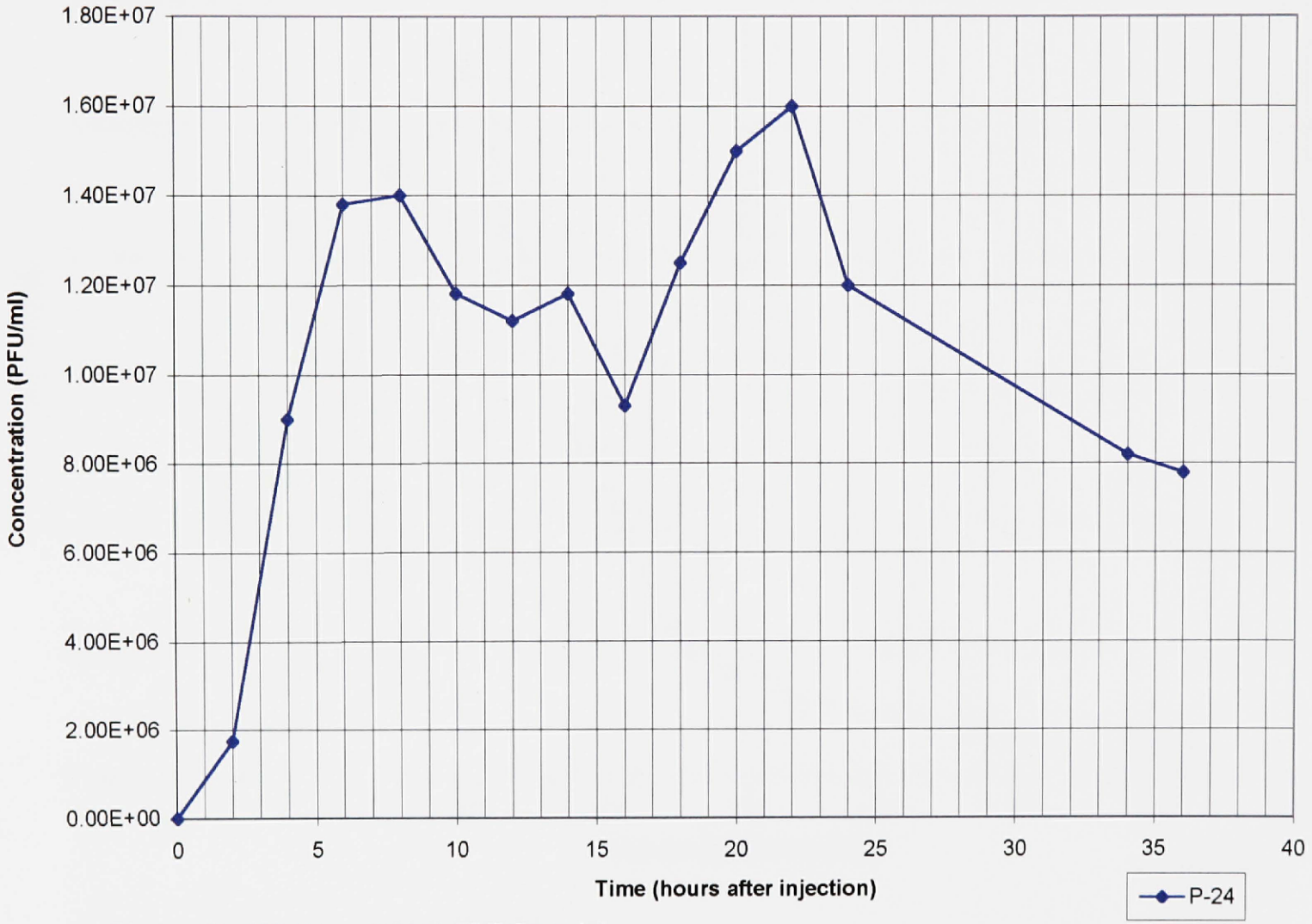


Figure 20. MS-2 tracer test 23 ft from I-4.

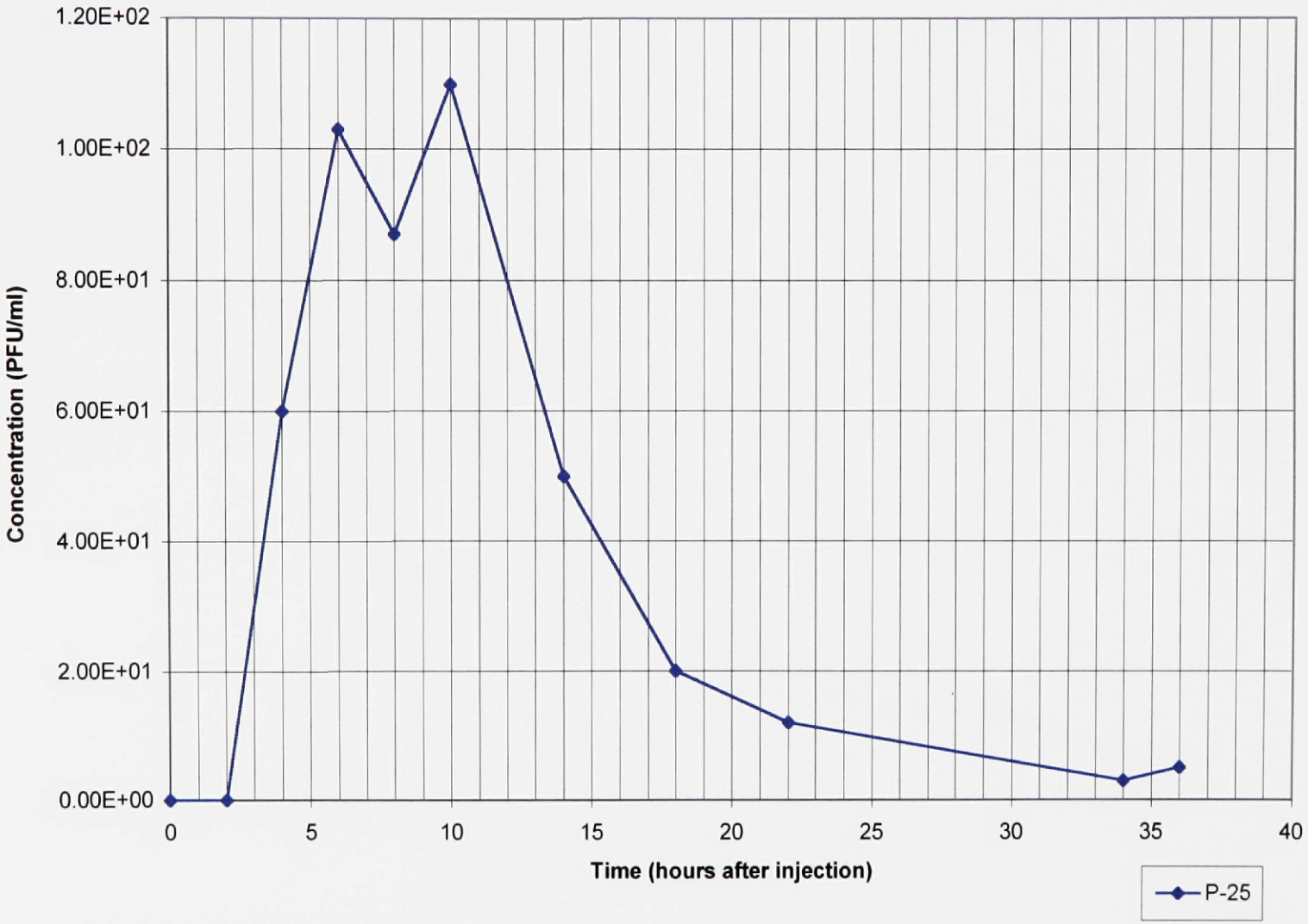


Figure 21. MS-2 tracer test 27 ft from I-4.

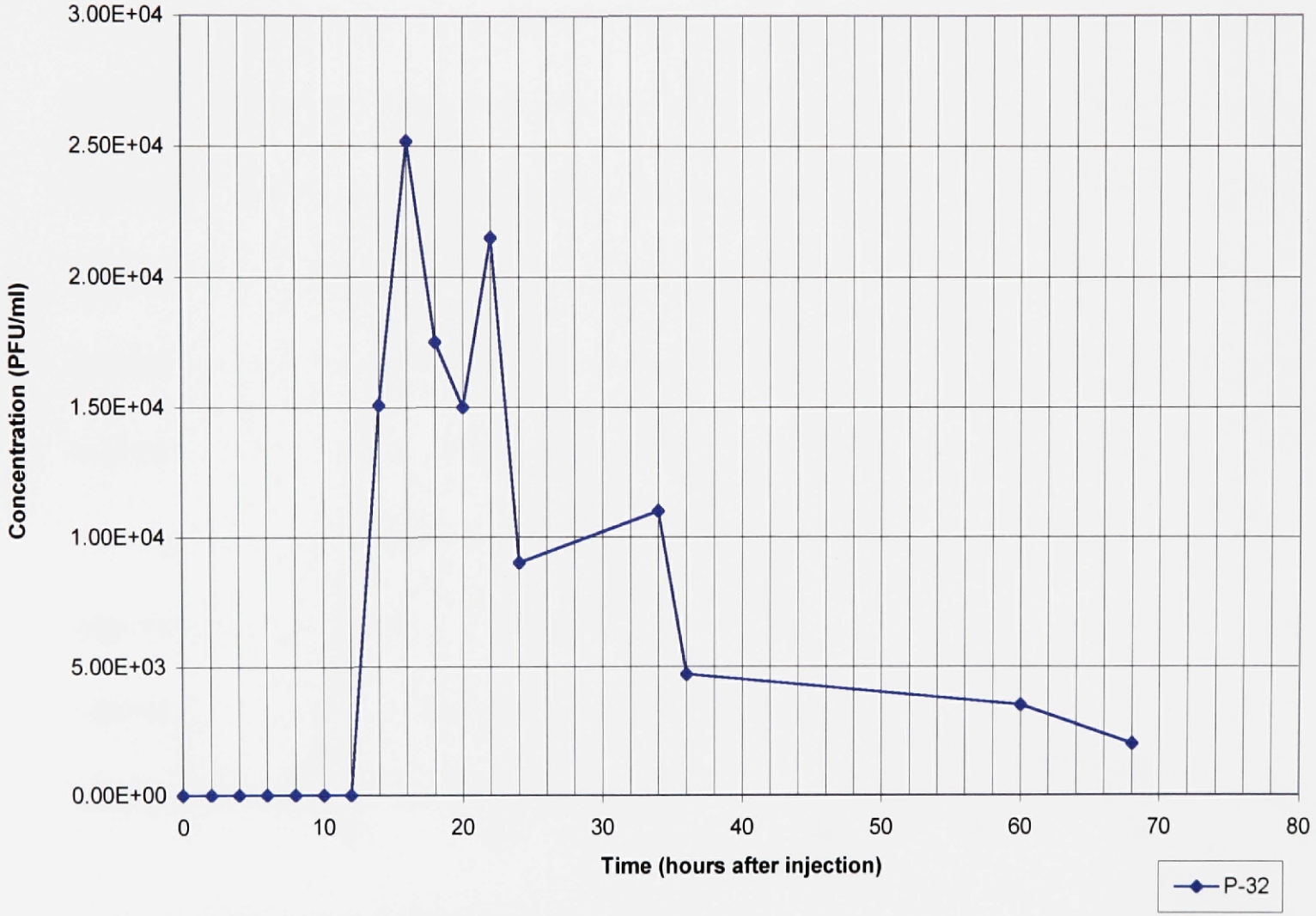


Figure 22. MS-2 tracer test 55 ft from I-4.

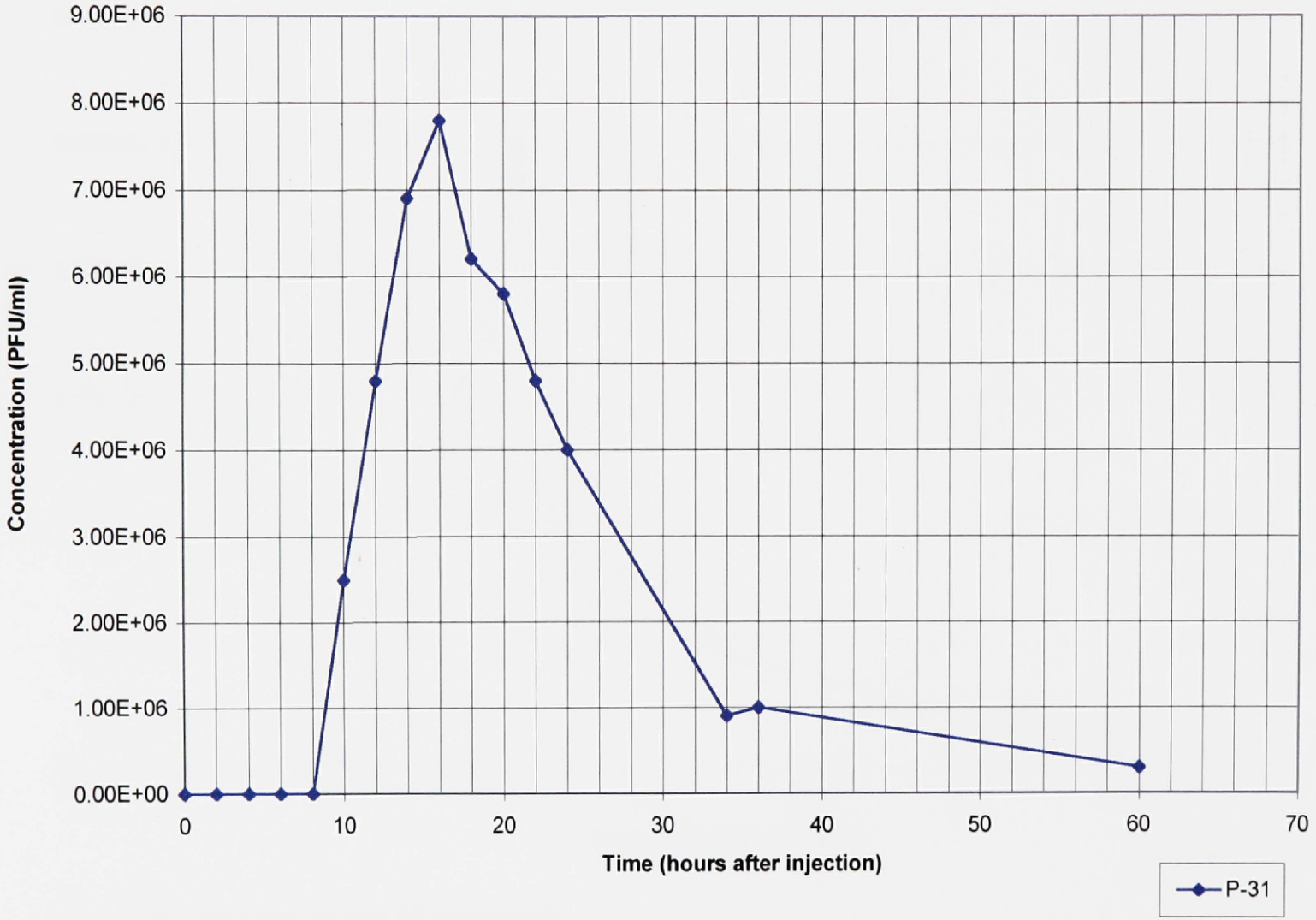


Figure 23. MS-2 tracer test 66 ft from I-4.

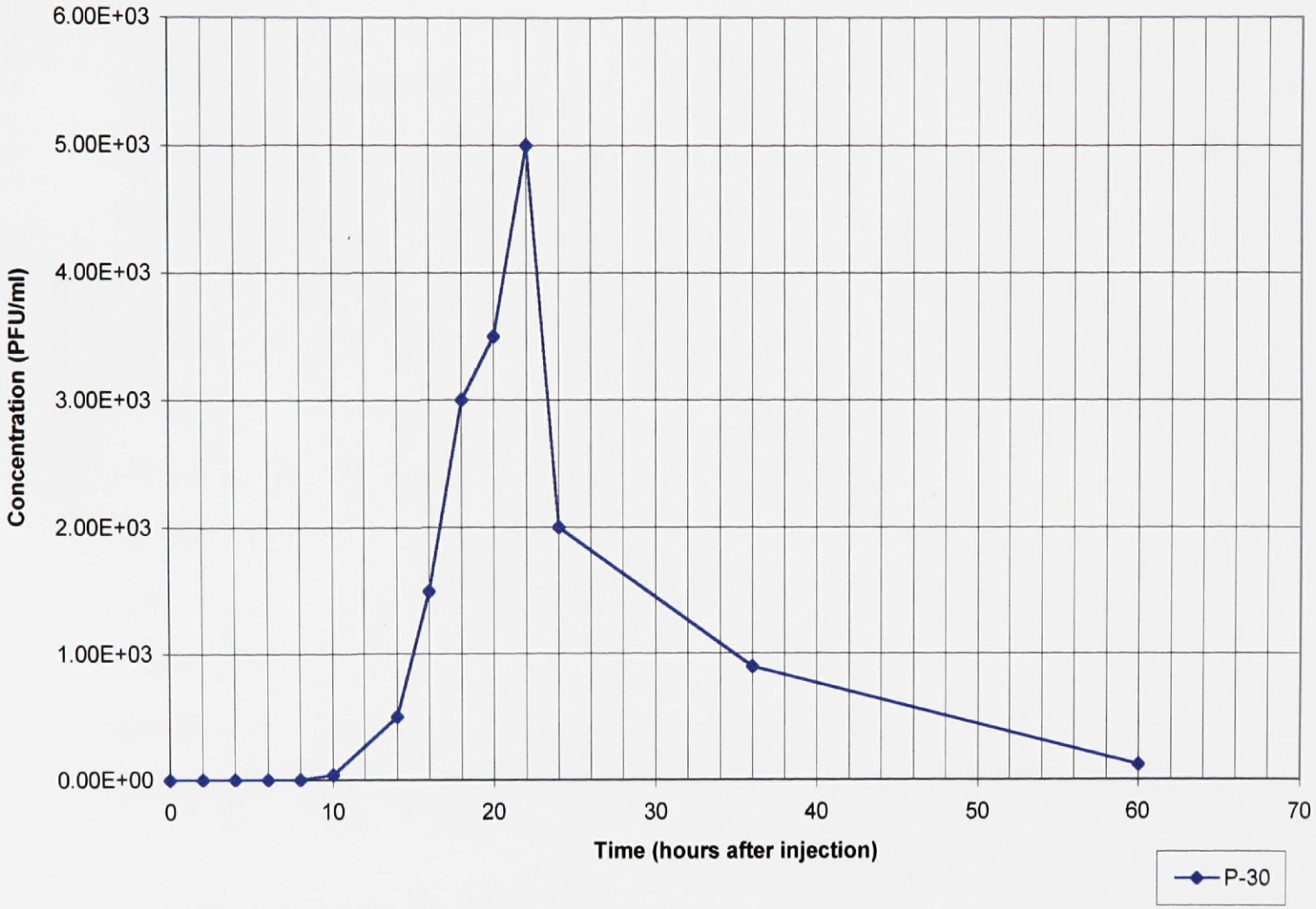


Figure 24. MS-2 tracer test 77 ft from I-4.

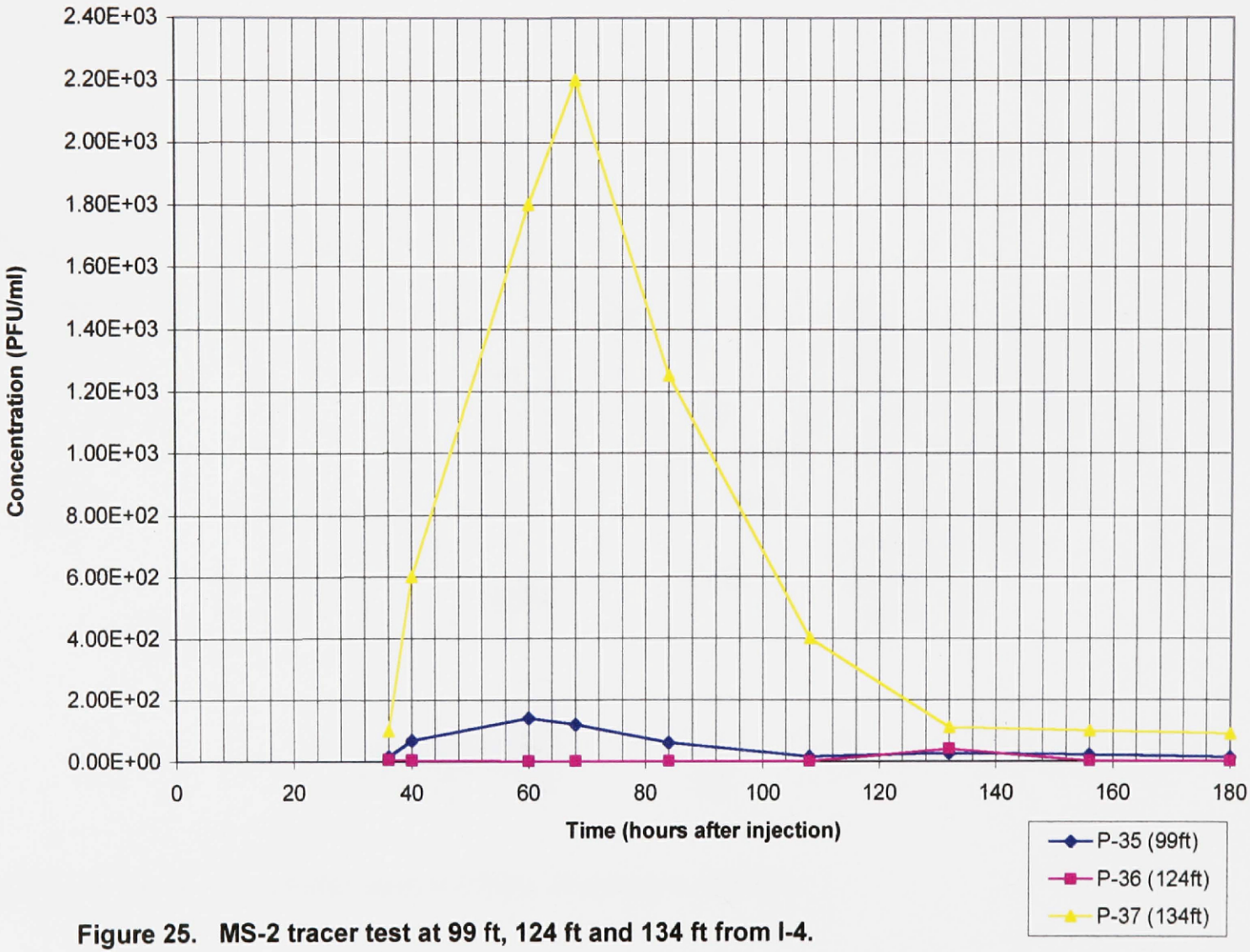


Figure 25. MS-2 tracer test at 99 ft, 124 ft and 134 ft from I-4.

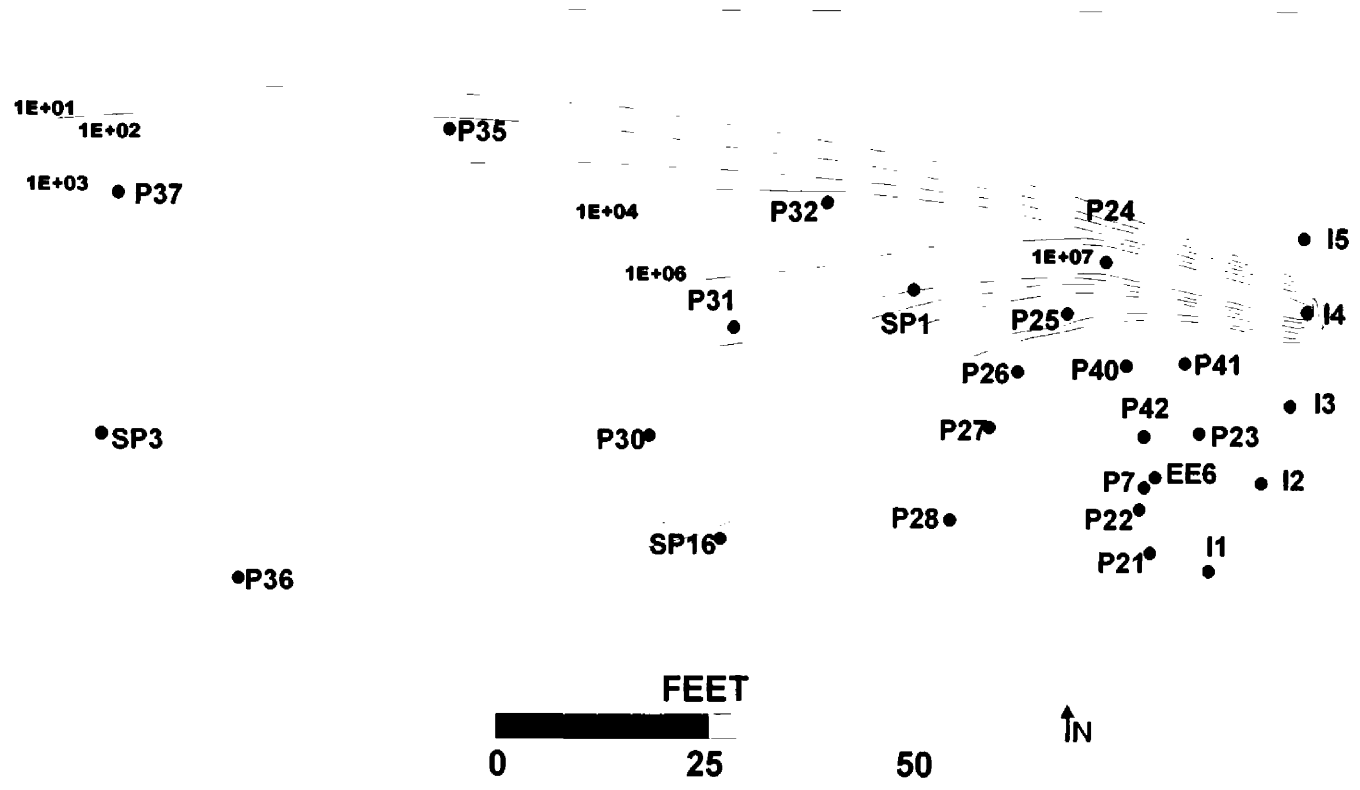


Figure 26. MS-2 plume 36 hours after injection 3/29/96, concentration in PFU/ml.

5.0 Discussion

The complex depositional environment of a large river floodplain produces a heterogeneous distribution of sediments and corresponding hydraulic conductivities at this site. Table 9 shows the wide range of hydraulic conductivity values throughout the site, suggesting a very heterogeneous flow field. A zone of extremely high hydraulic conductivity of greater than 30,000 ft/d intersects the injection well I-4 and wells P-24 and P-31, creating a preferential flow path through the network.

5.1 Physical Controls on Transport

Although sediment samples from boreholes were analyzed, and stratigraphic sequences developed at six locations, the 3-dimensional stratigraphy is largely unknown at Erskine, due to the point character of the data. The coarse-grained, large diameter deposits (greater than 2 to 3 inches) precluded the collection of undisturbed samples. At the Hanford Department of Energy site in south-central Washington, sediments of the Columbia River floodplain were examined by Poeter and Gaylord (1990). They found that although the development of lithofacies maps were useful in defining large-scale contaminate pathways, they were not detailed enough to serve as accurate predictors of the contaminant paths in the heterogeneous aquifer. Poeter and Gaylord (1990) suggest alternate techniques for collecting samples during drilling that allow for improved estimates of aquifer heterogeneity, such as degree of cementation, packing arrangement, sedimentary structures and grain shape. Boggs et al (1992) also used a variety of direct and indirect techniques to estimate spatial variability of hydraulic conductivity in an alluvial aquifer. Using a 3-dimensional network and a borehole flowmeter to sample four different tracer types, they found evidence of heterogeneities at several scales. Gernereux

Table 9. Hydraulic conductivity values calculated using various methods.

Well #	K (ft/day)	Log 10	Source
P-24	12267	4.1	Bromide tracer
P-31	28364	4.5	Bromide tracer
P-24	36800	4.6	Bromide tracer
P-31	26000	4.4	Bromide tracer
P-24	10036	4.0	MS-2 tracer
P-25	25920	4.4	MS-2 tracer
P-35	16640	4.2	MS-2 tracer
P-36	8945	4.0	MS-2 tracer
P-37	19059	4.3	MS-2 tracer
P-30	39600	4.6	MS-2 tracer
P-31	33000	4.5	MS-2 tracer
P-32	33600	4.5	MS-2 tracer
EE-5	1522	3.2	Slug test
EE-5	1568	3.2	Slug test
EE-5	1848	3.3	Slug test
EE-6	2462	3.4	Slug test
EE-6	2299	3.4	Slug test
EE-6	1437	3.2	Slug test
M2-9*	46512	4.7	Bromide tracer
M7-9*	42681	4.6	Bromide tracer
W2*	121987	5.1	W1 pumping test
SP1*	32392	4.5	W1 pumping test
SP24*	41615	4.6	W1 pumping test
M5*	19834	4.3	W1 pumping test
M6*	13759	4.1	W1 pumping test
M7*	31866	4.5	W1 pumping test
M9*	52100	4.7	W1 pumping test
M15*	3386	3.5	W2 pumping test
M14*	2889	3.5	W2 pumping test
M13*	2755	3.4	W2 pumping test
M12*	3389	3.5	W2 pumping test
M11*	3728	3.6	W2 pumping test
M10*	3321	3.5	W2 pumping test
SP24*	4578	3.7	W2 pumping test
SP3*	4247	3.6	W2 pumping test
W3*	3702	3.6	W3 pumping test (Theim)
W0*	404	2.6	W0 pumping test (Theim)
W0*	2587	3.4	W0 pumping test (Theis)
W1*	2621	3.4	W1 pumping test (Theis)
W2*	736	2.9	W2 pumping test (Theis)
W3*	658	2.8	W3 pumping test (Theis)

* from Kiley (1997)

and Guardiario (2001) also cite the use of an electromagnetic borehole flowmeter to estimate hydraulic conductivity at different depths in an unconfined aquifer. The vertical profiles, spaced 6 feet apart laterally, led to comparative analyses of both vertical and horizontal K values, showing zonal anisotropy.

Magruder's GPR (1998) along with the application and interpolation of seismic, EM, and extended drilling data, revealed the site contains subsurface strata characteristic of point bar deposits that are likely to contain gravel deposits of extremely high hydraulic conductivity. Ground-penetrating radar data appear to show stratification formed by a lateral accretion point bar, with preferential flow zones forming in the coarse-grained layers, influencing tracer behavior. Although the GPR did not correlate with specific grainsizes and sorting within the deposits, it is adequate in identifying types of shallow stratigraphic features on a larger scale.

The seismic refraction survey allowed determination of the general depth to water and the presence of a finer sand unit at the aquifer base. Additional aquifer stratigraphic detail was not discernible using seismic refraction. Leibundgut et al (1992) report the use of Very Low Frequency-Resistivity (VLF-R) and refraction seismic surveys as a useful tool not only for detailed resistivity and transmissivity mapping, but also for determining the thickness and degree of variability in a formation. Application of this tool at Erskine may improve the interpretation of the site geology.

Evaluating aquifer physical characteristics throughout a particular site is important in predicting not only preferential groundwater flowpaths, but also transport velocities, and how these properties influence both tracer and virus transport. Analyzing the factors that control virus transport in groundwater is very complex. Not only is it

difficult to quantify virus interactions with the aquifer, but characterizing such a heterogeneous system itself is complicated.

5.2 Tracer Behavior

Tracer tests were used initially to determine flowpaths and groundwater velocities and to establish appropriate sampling schedules.

Rhodamine WT dye was used as a quick and inexpensive tool to identify flowpaths and design sampling intervals for future tracer tests. Sutton et al (2001) show the presence of two isomers in the commercial dye, both with distinct emission spectra, which result in two separate breakthrough peaks as the isomers become separated during transport. Results from RWT tracer tests could be interpreted as either heterogeneities in the aquifer, or different arrival times for the isomers. Thus, the use of rhodamine to quantitatively interpret transport properties may be impacted by its non-conservative properties.

During this study, the initial RWT tracer injection into I-3 defined a groundwater flowpath, but the sampling was not frequent enough to provide accurate breakthrough data. The bromide tracer test also delineated the same groundwater flowpath from I-3, but the breakthrough curves differed greatly from the RWT experiment. At wells P-25 and P-31, the bromide peaked at 26 hours and 34 hours respectively, while the RWT peak arrived at 44 hours for both wells. Bromide peak concentrations were higher at P-31 than for P-25, although P-31 is 38 feet farther away from the injection site. Again, the sampling interval may not have been adequate to produce an accurate breakthrough curve for P-25, or the center of mass may have missed the closer well.

Since the rhodamine tracer injected into I-5 was not detected in any monitoring

wells, no breakthrough data were collected. However, these results suggest either the presence of a partial barrier of very low K separating I-5 from the rest of the flowfield, or a groundwater divide in the system, with flow heading in a more northerly direction from the main flowfield.

The subsequent bromide tracer tests using injection well I-4 showed consistency in analyses of P-31 data, with the peak arriving at 22 and 24 hours. However, in all the bromide and MS-2 tracer tests, the breakthrough curves for P-24 revealed a dual peak in each instance, with the arrival times varying several hours in each event. If this pattern appeared in only the MS-2 experiment, it would indicate that sorption and subsequent desorption of the virus in the aquifer matrix was taking place. Since this occurred with both the tracer and bacteriophage tests, data suggest a physical control, perhaps particle migration into and out of lower velocity sediments, or a re-release of the tracers from the injection well area. A small-scale lens of lower hydraulic conductivity downgradient could cause a secondary, higher concentration to develop at P-24 after the initial peak passed through, but this is highly unlikely in such coarse-grained sediments.

5.3 Influences on Virus Transport

As this work represents the initial investigation in a series of tracer experiments, well location, depth and sampling frequency may have interfered with deciphering the specifics of MS-2 behavior at this site. However, assuming sampling times and well locations relative to plume position were adequate, I present the following observations.

Concentrations of bromide and MS-2 were normalized and plotted in Figures 27 and 28 to compare relative concentrations after injection. Not only does the bacteriophage peak appear to arrive sooner in both cases, but it also had a higher

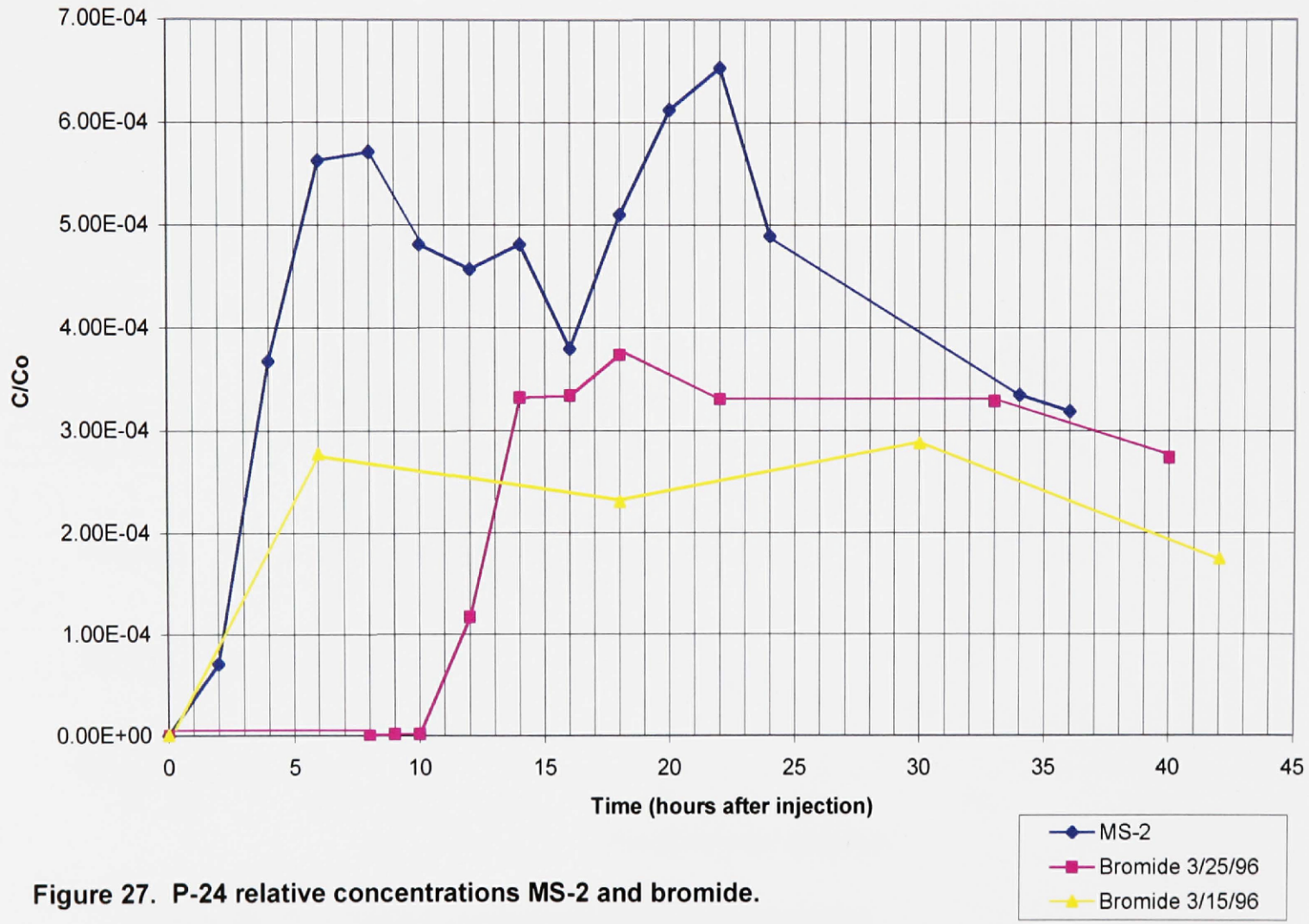


Figure 27. P-24 relative concentrations MS-2 and bromide.

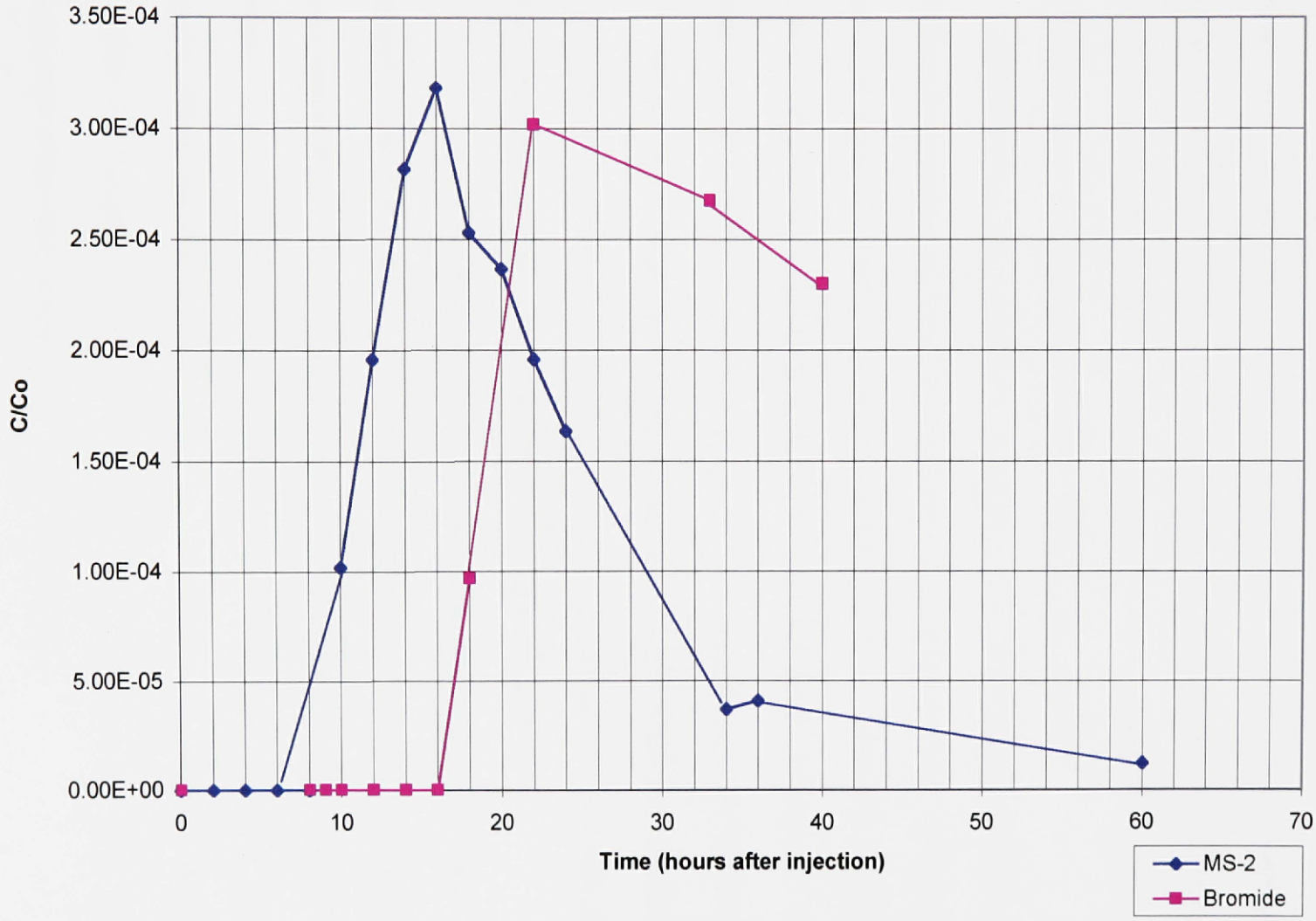


Figure 28. P-31 relative concentrations MS-2 and bromide.

normalized concentration as well. Density effects of bromide may account for this loss in concentration, but does not explain the lag time for the breakthrough curves. Kiley (1997) reported slight vertical bromide migration at the site of less than 6 feet below the water table over 100 feet of horizontal transport. Harvey and Gorelick (2000) present a mass transfer model to describe similar concentration profiles, suggesting that a combination of nonequilibrium mass transfer (molecular diffusion into and out of low permeability zones) and chemical sorption control plume behavior.

Bromide is an ion measuring 1.96 angstroms in diameter and therefore able to travel through pore sizes down to the molecular level. MS-2 is 25nm in diameter and is subject to pore size exclusion (Pekdeger and Matthess 1983). Virus flow is therefore restricted to larger pore channels that may have a shorter effective flow path. The bromide may have diffused into dead-end pores or succumbed to sorptive processes. The lack of fine sediments in preferential pathways, coupled with extremely high groundwater velocity, may have precluded any measurable MS-2 adsorption. In any event, there was surprisingly less attenuation occurring with MS-2 than the bromide.

Harvey et al (1993) compared microorganism transport behavior with conservative tracers bromide and chloride in heterogeneous aquifers, finding that physical variability in aquifer structure increases dissimilarity between transport behaviors. It was concluded that variability in aquifer structure, along with sorption processes, affects microbial transport behavior. As reported in this study, Bhattacharjee et al (1999) and Powelson et al (1993) also found that some fraction of the viruses always break through either with, or ahead of, conservative tracers.

5.5 Groundwater Disinfection Rule

Dutka et al (1990) report an increasing presence of coliphage in treated drinking water, both tap and bottled, suggesting that human enteric viruses survive normal treatment processes. Potential sources of pathogenic bacteria and viruses include septic tanks, landfills, leaking sewer pipes, land application of sewage sludge, irrigation with wastewater, and deep well injection of sewage.

Virus concentrations of untreated sewage effluent are 10^2 - 10^4 PFU/L (Matthess and Pekdeger 1985). Yates and Jury (1995) consider one infection per 10,000 persons/year to be an acceptable risk, equating to a virus concentration of $<2 \times 10^{-7}$ virus/L. According to Matthess and Pekdeger (1985) treated drinking water must contain only 1 infectious unit per 10^5 - 10^8 L, so there must be a 7-log decrease in units before the untreated water is usable as drinking water. The new EPA regulation only requires a 4-log inactivation or removal of viruses in source water to be considered potable. The natural gradient MS-2 tracer test at Erskine showed a 4-log decrease between 66 and 77 feet from I-4, and a 7-log inactivation at 134 feet from the injection well. Therefore, the initial concentration of the contaminant is important when evaluating setback distances from a potential virus source, and determining if the pathogen level is low enough to no longer pose a significant health risk. Yates and Yates (1988) present an equation to determine separation distances between a contaminant source and wellhead:

$$\mathbf{D = tKi/n_e}$$

D = separation distance
t = travel time required for 7 logs of virus inactivation
K = hydraulic conductivity
i = hydraulic gradient
n_e = effective porosity

Applying this equation to the Erskine site, and assuming a K value of 30,000 ft/d, a 7-log decrease from the initial concentration (measured in the injection well) of 2.45E+10PFU/L would mandate a setback distance of 216 feet. Even in this cold, coarse-grained aquifer, MS-2 was attenuated to an acceptable level between 66 and 77 feet from the injection site to meet the 4-log inactivation requirement of the GWDR. However, the effects of a pumping well must be taken into account to calculate a more accurate natural disinfection distance/time at the site.

5. Conclusion

Public health concerns dictate detecting and monitoring transport of pathogenic bacteria and viruses in groundwater. A main obstacle is determining the factors controlling waterborne pathogen concentrations in drinking water supplies.

The following are conclusions derived from this research:

1. The floodplain aquifer at the Erskine Fishing Access site is coarse grained and has a complex architecture and hydraulic conductivity distribution that may be well correlated.
2. Ground-penetrating radar analyses suggest the shallow aquifer instrumented for the tracer test is a lateral accretion point bar deposited by a fluvial system.
3. Hydraulic conductivity varies widely from 400 to 120,000 ft/d with a log variance of 0.38. Tracer test analyses indicate velocities range from 20 to 92 ft/d.
4. Rhodamine WT dye was useful in detecting groundwater flowpaths and approximating tracer sampling frequency for future experiments. It most likely acts non-conservatively and thus may not be as useful as bromide in assessing physical controls on transport.

5. The use of bromide as a tracer in this environment represented complex behavior of a conservative ionic tracer. Double peaks on breakthrough curves were observed, implying transport in both high and low velocity zones.

6. Seeded MS-2 was detectable over distances of 134 feet, a greater distance than bromide detection at 65 feet. This suggests bacteriophage make good tracers for highly conductive groundwater systems.

7. Virus peak breakthrough, within the sampling frequency used, arrived sooner than the bromide.

8. The normalized concentrations (C/Co) of MS-2 as compared to bromide values show more MS-2 reached the observation wells. This suggests preferential flow and possible pore exclusion of the virus. The higher observed C/Co for MS-2 implies that bromide tracer data alone may not be adequate to suggest possible peak virus concentrations.

9. A setback distance of 100 feet in this coarse grained, high velocity groundwater system meets the proposed Ground Water Rule requirement of a 4-log virus reduction. However, the 7-log inactivation proposed by Yates and Yates (1988), Matthess and Pekdeger (1985), and Yates and Jury (1995) would not be met until transport of more than 134 feet occurred.

10. The source concentration of viruses should be considered in any Ground Water Rule adopted.

Recommendations:

1. Refine interpretation of distribution of sediments and the corresponding distribution of hydraulic conductivity: 1) apply additional geophysical techniques such as seismic Very

Low Frequency-Resistivity and Refraction; 2) attempt coring using 2-inch diameter Geoprobe sampler or 4-inch diameter rotosonic drilling techniques; and 3) conduct borehole flowmeter tests in fully screened wells.

2. Refine tracer distribution data and breakthrough curves: 1) expand the observation well network to include multi-level samplers along the main flowline from I-4 and at right angles to its flow; and 2) apply shorter sampling time intervals.

3. Examine the virus-specific properties that influence transport: 1) conduct natural gradient bromide and multiple virus tracer experiments, with use of bacteriophage commonly reported in the literature at field sites and, if permitted, one or more enteric viruses; and 2) conduct both natural gradient and forced gradient experiments to examine how pumping affects virus transport.

In order to comply with the Ground Water Rule, it is necessary to identify the types of pathogens most likely to occur at wellheads, and the physical and viral-specific factors controlling their transport and fate. There is a potential health threat associated with low numbers of viruses, so caution should be used when extrapolating results from one site to another. Since each area is unique, site-specific information is needed to accurately predict appropriate setback distances and protect consumers from contaminated source water.

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Appendix A

The Groundwater Disinfection Rule

The Total Coliform Rule is currently the only federal regulation directly governing the presence of microbes in public groundwater systems, though it only requires testing for coliform bacteria, not for viruses (USEPA 2000). Therefore, the EPA has proposed the Ground Water Disinfection Rule to protect public water supplies that use groundwater as their source, from both bacteria and viruses. This policy, scheduled to be released as a final regulation this year, requires the mandatory treatment of public water supplies unless "natural disinfection" occurs between a potential contaminant source and the pumping well.

In order to obtain an exemption from disinfecting their water supplies, Adelman et al (1998) describe the four options public water utilities have to demonstrate natural disinfection will occur between a contaminant source and a municipal well: 1) The time it takes for groundwater to travel from a virus source to a well is sufficient for virus die-off to recommended levels. 2) The time it takes for a virus particle to travel from its source to a well is sufficient for virus inactivation to recommended levels. 3) A hydrogeologic feature exists to control contaminant flow to the well, and human activities will not adversely affect the integrity of that feature. 4) The necessary setback distance exists between a virus source and well for the viruses to die off.

The relatively high costs of purifying groundwater, along with possible toxic effluents from chemical disinfection, make natural disinfection desirable. Lazarova et al (1999) reviewed overall effectiveness of water disinfection processes including

chlorination, ultraviolet irradiation, ozonation and membrane filtration. Traditional chlorination methods produce toxic by-products when naturally occurring organic matter reacts with chlorine and form carcinogenic compounds, so subsequent dechlorination of drinking water is advisable. Ultraviolet irradiation and ozonation are more effective disinfection techniques for bacteria and viruses, and do not produce secondary toxic effluents, but require equipment retrofitting. Membrane filtration is the only technology that guarantees total disinfection with no toxic side effects, but has a very high cost.

Two primary problems exist with protecting wells from viral contamination. Not only are viruses difficult and expensive to detect, they require much more extensive disinfection measures than other microbes. Detection and identification of viruses is difficult due to lack of available methods and facilities to analyze samples, and many water utilities do not have these capabilities. It is also an expensive, time-consuming process, involving isolation of tissue cultures and requiring a specific antibody for each virus type. There is a potential health threat associated with low numbers of viruses, so it is necessary to sample large volumes of water (40 to 1000L) in order to detect the pathogens (Gerba 1988). Gerba et al (1989) suggest an application of gene probes as an alternative to detect the presence of viruses in water and other samples. Gene probes are strands of nucleic acid labeled with radioactive or non-radioactive compounds that identify the genetic information of any organism. One probe can detect related viruses at a very low detection limit, but it cannot determine the infectivity of the viruses.

The coliform bacteria *Escherichia coli* is often used as an indicator organism for the presence of other enteric bacteria, since they are commonly found together, but research shows coliforms are not reliable indicators of viral presence; the lack of coliform

bacteria in groundwater does not always correlate with the absence of viruses. Due to their much larger sizes, bacteria are generally easier to detect and trace in porous media than are viruses. Bacteria species can be viewed under light microscopy and are relatively easy to identify through established series of tests, but Nasser et al (1993) found that *E. coli* die-off is greater than virus in groundwater, especially at low temperatures (10°C), making it an unsuitable indicator of viral persistence. In many outbreaks, viruses exist in treated, chlorinated water, even in the absence of fecal coliform bacterial contamination (Hejkal et al 1982, Keswick and Gerba 1980). Marzouk et al (1980) also investigated the validity of using indicator bacteria to predict virus occurrence in water, finding that elimination of bacteria to safe levels, through treatment or natural die-off, would still leave large numbers of pathogenic enteric viruses. This not only indicates that water meeting bacteriological standards may not be virus-free, but bacterial pathogens cannot be used as reliable indicators of human enteric viruses (Kukkula et al 1997).

Appendix B

Site Stratigraphy

Well Boring Logs

Six boreholes were initially drilled at the site using a 7 3/4" hollow-stem auger. EE-1 was drilled to a depth of 50 feet, with the remaining five (EE-1 to EE-6) to a depth of 18 to 21 feet. Samples were taken from augered cuttings with a 2 1/2" split-spoon sampler, and described in Tables B-1 to B-6.

Grain Size Analyses

Grain size distributions were calculated from the borehole samples collected during drilling of the initial EE wells. All sediment samples were sieved in the lab, using U.S standard sieves and scaled according to the Wentworth classification. Uniformity coefficients (Cu) ranged from 2 to 42, with most of the sediments poorly sorted.

Sediments obtained from the 50-foot borehole (EE-1) at depths of 5ft, 10ft and 15 ft below land surface were analyzed in Tables B-7 to B-9, and grain size distributions plotted in Figures B-1 to B-3. One sample was collected and analyzed for EE-2 at a depth of 18ft (Table B-10, Figure B-4). Samples were taken in the four remaining boreholes (EE-3, EE-4, EE-5 and EE-6) at a depth of 21ft as shown in Tables B-11 to B-14 and Figures B-5 to B-8.

Table B-1. EE-1 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
3.9	water table
5	sandy gravel, some cobbles
	poorly sorted, sub-rounded gravels 1/4 -1 1/2"
	poorly sorted, fine to coarse sand
	minor organics, silt
10	gravels to gravelly sand
	75% fine to coarse sand, mostly coarse
	25% rounded to sub-rounded gravels 1/4 - 3/4"
15	sandy gravels and cobbles
	60% rounded to sub-rounded gravels 1/4 - 1 1/2"
	35% poorly sorted, fine to coarse sand, mostly coarse
	5% rounded, broken cobbles >2"
20	no sample, heaving sands
	(driller reports easy drilling)
25	fine to coarse sand, some gravel
	center plug sample fine to medium sand
	gravels probably small sub-rounded to rounded 1/4 - 1"
	***aquifer base**
30	as above, no sample
32-34	gravels 1/2 - 3/4"
35	no sample, heaving sands, soupy, gravelly
	fine to coarse sand, gravels 1/4 - 1 1/2"
40	fine to coarse sand, gravels 1/4 - 1 1/2"
42-44	gravelly lens
45	lt. brown, cohesive clays
	gravels 1 -1 1/2" (clay may host gravel - uncertain)
	water flowing from borehole at surface 1-2 gpm
	(upward gradient)
50	as above, gravelly sand and silt, minor clay
	silt & clay probably 42 - 50 ft

Table B-2. EE-2 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
0-1	soil
4.26	water table
5	silty, sandy gravel
10	silty, sandy gravel with decreasing silt
18	sandy gravel
	65% coarse gravel
	total depth

Table B-3. EE-3 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
0-3	soil, silt and loam
3-3.5	small, thin gravel lens in sand
4.72	water table
3.5-7	gravelly sand
7	increasing gravels > sandy gravel 90% well-sorted, well rounded to sub rounded gravel 3/4-2" 10% fine to coarse sand
13	100% well-rounded gravels, moderately well sorted, very few fines 1/2-2"
18	as above
21	total depth

Table B-4. EE-4 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
0-1	soil, silt and loam
3.64	water table
5	gravelly sand
	75% fine to coarse sand, mostly medium
	25% gravels, rounded to sub rounded 1/4-2"
10	sandy gravel
	70% gravels, rounded to sub rounded 1/4-2"
	30% medium sand, little or no fines
15	as above
	decreasing sand
21	sandy gravel, predominantly rounded to sub rounded 1/4-2"

Table B-5. EE-5 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
0-1	soil, silt and loam
1-5.5	gravel, minor sand 90-95% well sorted, well-rounded gravels 1/4-2" predominantly 1"
5.59	water table
6	gravel, minor sand 90-95% well sorted, well-rounded gravels 1/4-2" predominantly 1"
9	gravel, minor sand, as above
10	sandy gravel, sub rounded to well rounded, predominantly 1"
13	sandy gravel, sub rounded to well rounded, predominantly 1"
21	sandy gravel, sub rounded to well rounded, predominantly 1" total depth

Table B-6. EE-6 well boring log.

All measurements in feet below land surface.

Depth	Description
Surface	flat pasture, little soil cover
0-1	soil, silt and loam
1-5.5	sandy gravel
	70% sub rounded to rounded gravels 1/4-2"
	30% fine to coarse sand
5.59	water table
	as above, decreasing sand, predominantly gravel
	80% well-sorted gravel
	20% sand, mostly 1-1 1/2"
11	80% well-sorted gravel
	20% sand, mostly 1-1 1/2"
18	as above, sandy gravel, some cobbles
21	total depth

Table B-7. EE-1 grain size analysis 5 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	2.92	0.0037
63u	2.5	0.0031
125u	4.54	0.0057
250u	24.56	0.0309
500u	26.72	0.0336
1mm	23.48	0.0295
2mm	29.97	0.0377
4mm	88.71	0.1116
8mm	392.65	0.4940
25mm	198.83	0.2501
38mm		
TOTAL	794.88	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.3674
0.063	0.3674	0.3145
0.125	0.6819	0.5712
0.25	1.2530	3.0898
0.5	4.3428	3.3615
1	7.7043	2.9539
2	10.6582	3.7704
4	14.4286	11.1602
8	25.5888	49.3974
25	74.9862	25.0138
38	100	

d60	d10	Cu
18	1.8	10

Table B-8. EE-1 grain size analysis 10 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	11.74	0.0059
63u	17.59	0.0089
125u	37.09	0.0187
250u	270.17	0.1363
500u	512.74	0.2586
1mm	112.74	0.0569
2mm	184.39	0.0930
4mm	325.8	0.1643
8mm	447.36	0.2257
25mm	62.85	0.0317
38mm		
TOTAL	1982.47	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.5922
0.063	0.5922	0.8873
0.125	1.4795	1.8709
0.25	3.3504	13.6279
0.5	16.9783	25.8637
1	42.8420	5.6868
2	48.5289	9.3010
4	57.8299	16.4340
8	74.2639	22.5658
25	96.8297	3.1703
38	100	

d60	d10	Cu
4.5	0.38	12

Table B-9. EE-1 grain size analysis 15 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	10.99	0.0243
63u	13.81	0.0305
125u	26.02	0.0574
250u	336.65	0.7432
500u	45.96	0.1015
1mm	11.45	0.0253
2mm	7.9	0.0174
4mm	0.17	0.0004
8mm		
25mm		
38mm		
TOTAL	452.95	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		2.4263
0.063	2.4263	3.0489
0.125	5.4752	5.7446
0.25	11.2198	74.3239
0.5	85.5437	10.1468
1	95.6905	2.5279
2	98.2183	1.7441
4	99.9625	0.0375
8	100	
25	100	
38	100	

d60	d10	Cu
0.39	0.25	2

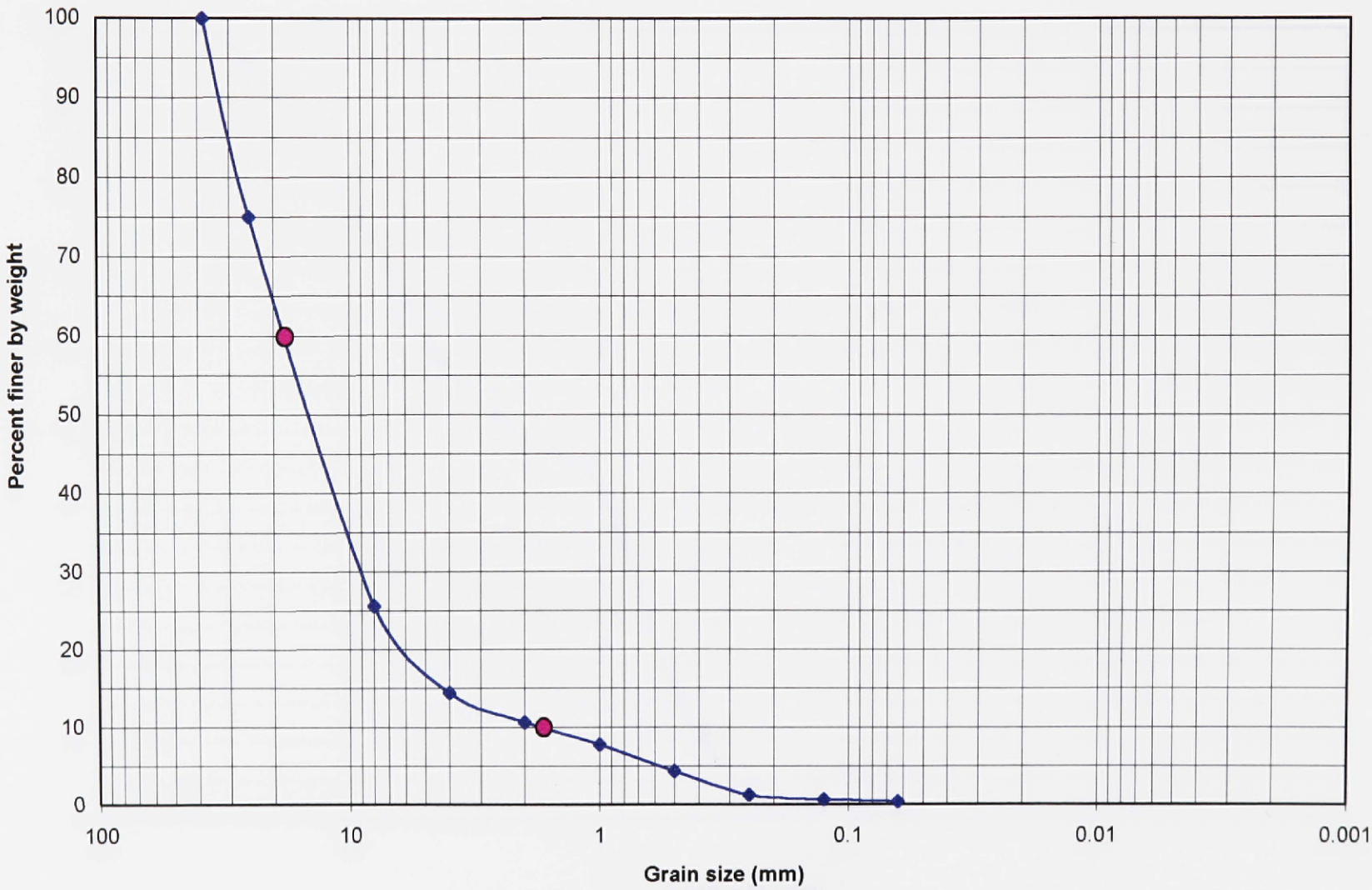

Figure B-1. EE-1 grain size distribution 5 feet below land surface.

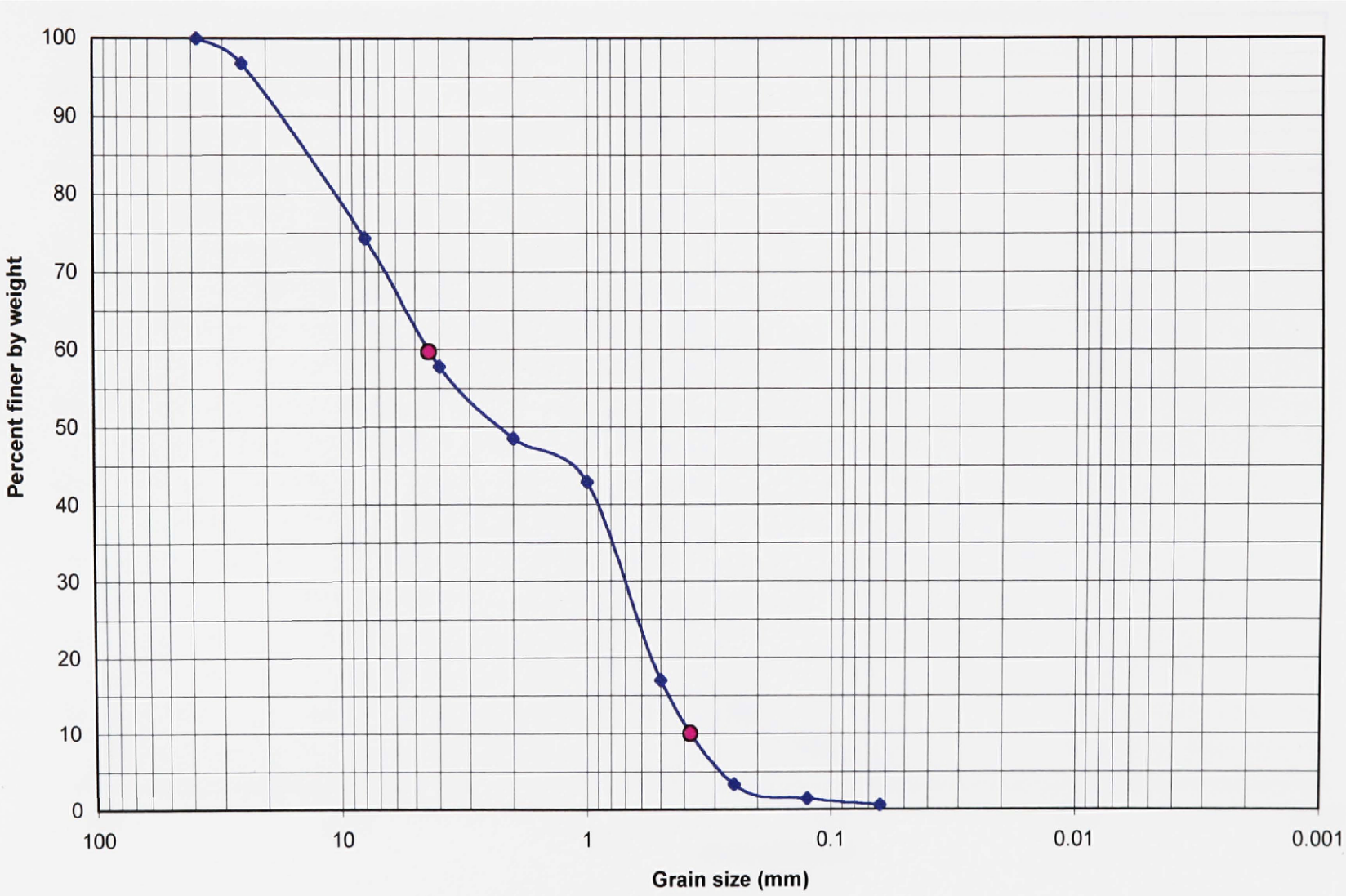

Figure B-2. EE-1 grain size distribution 10 feet below land surface.

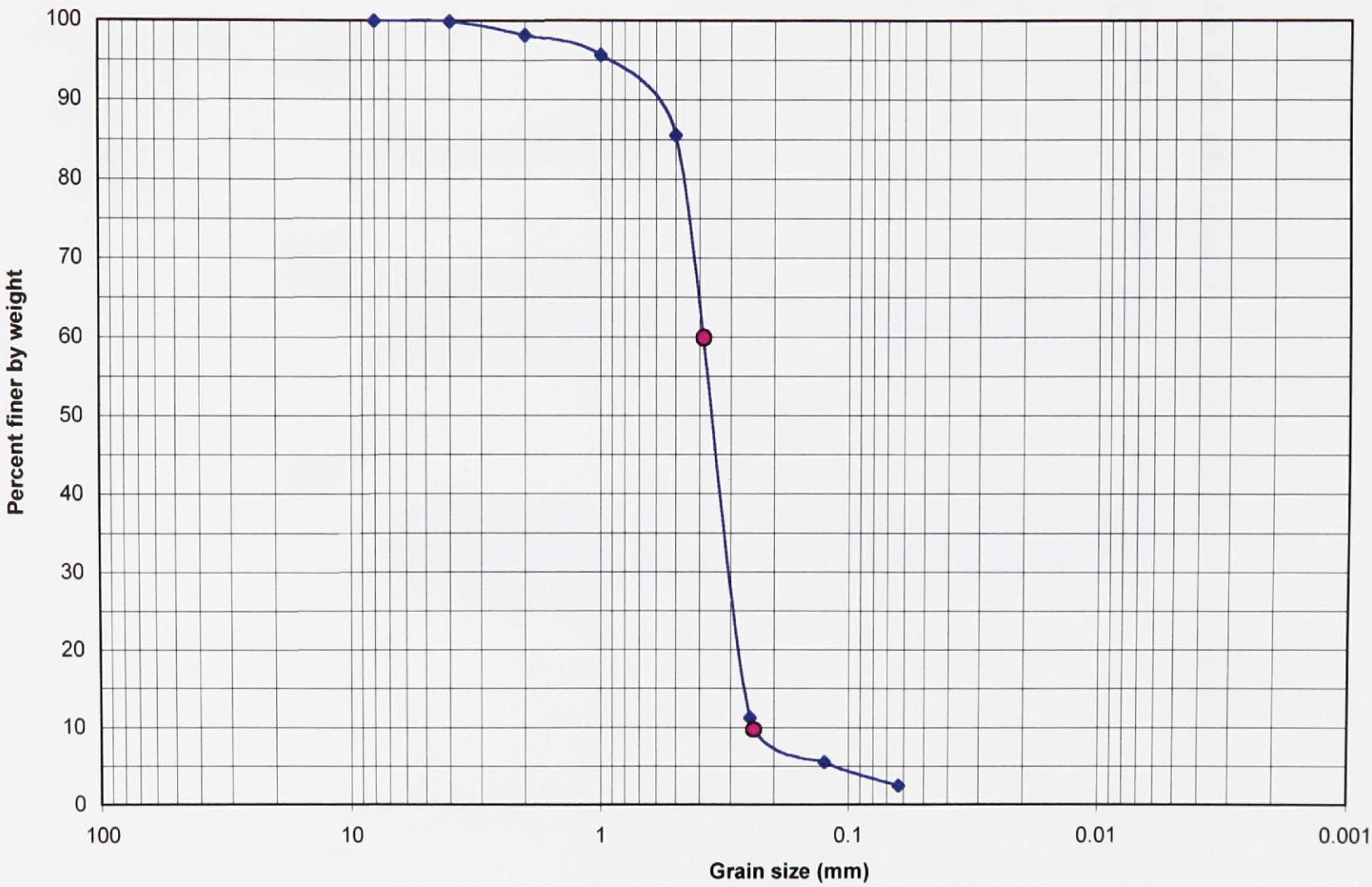

Figure B-3. EE-1 grain size distrubution 15 feet below land surface.

Table B-10. EE-2 grain size analysis 18 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	5.22	0.0049
63u	5.01	0.0047
125u	13.88	0.0131
250u	128.59	0.1218
500u	210.03	0.1990
1mm	40.88	0.0387
2mm	61.1	0.0579
4mm	129.38	0.1226
8mm	425.19	0.4028
25mm	36.33	0.0344
38mm		
TOTAL	1055.61	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.4945
0.063	0.4945	0.4746
0.125	0.9691	1.3149
0.25	2.2840	12.1816
0.5	14.4656	19.8966
1	34.3621	3.8726
2	38.2348	5.7881
4	44.0229	12.2564
8	56.2793	40.2791
25	96.5584	3.4416
38	100	

d60	d10	Cu
9	0.4	23

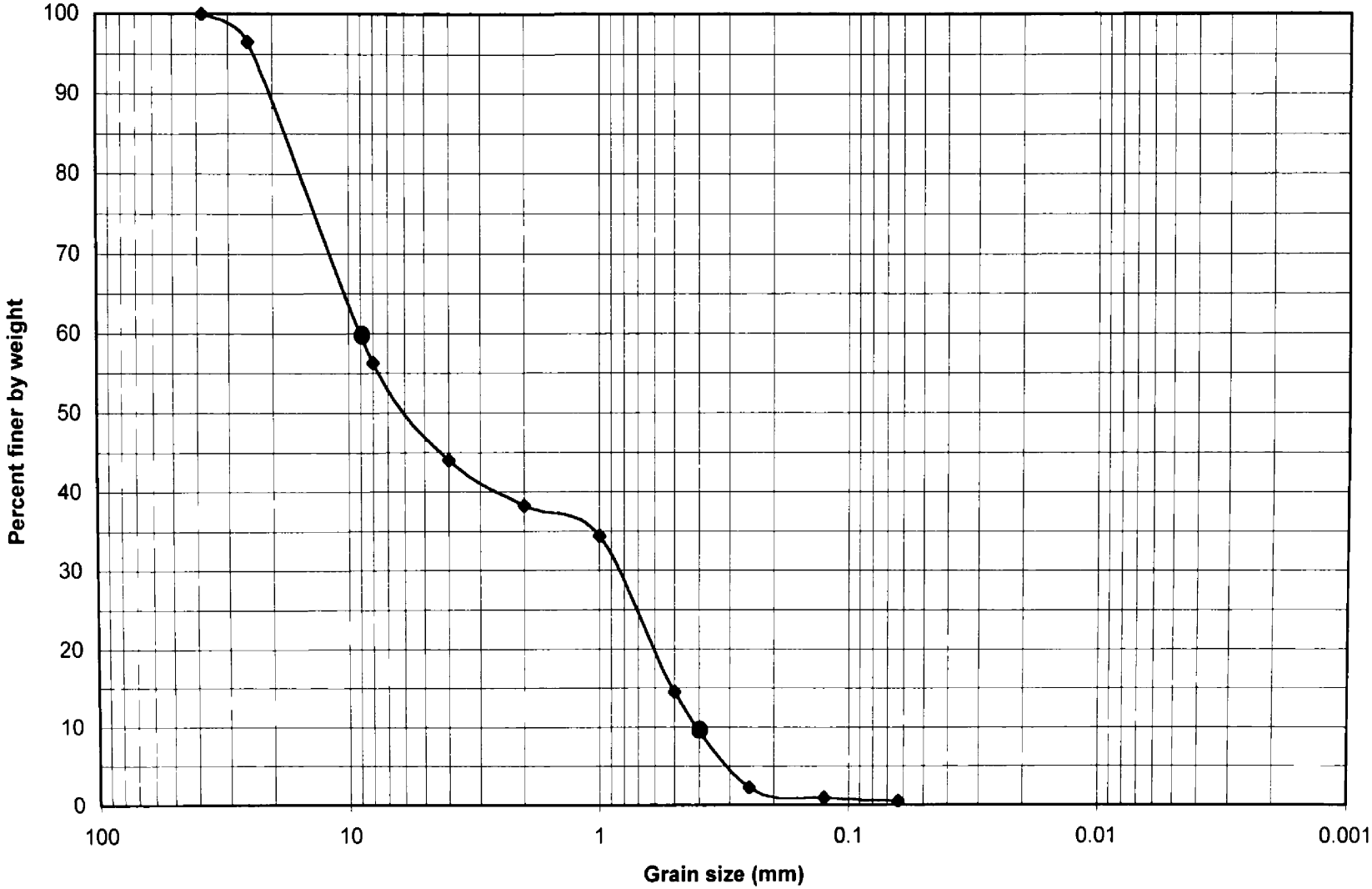

Figure B-4. EE-2 grain size distribution 21 feet below land surface.

Table B-11. EE-3 grain size analysis 21 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	9.37	0.0058
63u	12.3	0.0076
125u	18.91	0.0116
250u	279.79	0.1719
500u	285.72	0.1755
1mm	39.47	0.0242
2mm	51.53	0.0317
4mm	86.29	0.0530
8mm	424.05	0.2605
25mm	259.13	0.1592
38mm	161.34	0.0991
TOTAL	1627.9	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.5756
0.063	0.5756	0.7556
0.125	1.3312	1.1616
0.25	2.4928	17.1872
0.5	19.6800	17.5514
1	37.2314	2.4246
2	39.6560	3.1654
4	42.8214	5.3007
8	48.1221	26.0489
25	74.1710	15.9181
38	90.0891	9.9109
64	100	

d60	d10	Cu
15	0.36	42

Table B-12. EE-4 grain size analysis 21 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	10.49	0.0034
63u	18.84	0.0061
125u	56.08	0.0180
250u	356.02	0.1143
500u	317.41	0.1019
1mm	129.73	0.0417
2mm	194.02	0.0623
4mm	394.87	0.1268
8mm	1192.14	0.3828
25mm	333.6	0.1071
38mm	110.66	0.0355
TOTAL	3113.86	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.3369
0.063	0.3369	0.6050
0.125	0.9419	1.8010
0.25	2.7429	11.4334
0.5	14.1763	10.1935
1	24.3698	4.1662
2	28.5360	6.2309
4	34.7668	12.6810
8	47.4479	38.2850
25	85.7328	10.7134
38	96.4462	3.5538
64	100	

d60	d10	Cu
13	0.4	33

Table B-13. EE-5 grain size analysis 21 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	4.9	0.0020
63u	10.6	0.0044
125u	21.22	0.0088
250u	329.01	0.1367
500u	239.36	0.0995
1mm	80	0.0332
2mm	148.12	0.0615
4mm	311.22	0.1293
8mm	872.7	0.3626
25mm	23.58	0.0098
38mm	365.92	0.1520
TOTAL	2406.63	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.2036
0.063	0.2036	0.4404
0.125	0.6441	0.8817
0.25	1.5258	13.6710
0.5	15.1968	9.9459
1	25.1426	3.3242
2	28.4668	6.1547
4	34.6214	12.9318
8	47.5532	36.2623
25	83.8155	0.9798
38	84.7953	15.2047
64	100	

d60	d10	Cu
13	0.4	33

Table B-14. EE-6 grain size analysis 21 ft below land surface.

Grain size	Weight (gm)	Total wt. fraction
<63u	9.03	0.0030
63u	25.6	0.0085
125u	69.22	0.0229
250u	550.86	0.1824
500u	111.31	0.0369
1mm	121.04	0.0401
2mm	196.3	0.0650
4mm	397.65	0.1316
8mm	1198.21	0.3967
25mm	341.33	0.1130
38mm		
TOTAL	3020.55	1

Grain size (mm)	% finer by wt.	% total wt.
<0.063		0.2990
0.063	0.2990	0.8475
0.125	1.1465	2.2916
0.25	3.4381	18.2371
0.5	21.6752	3.6851
1	25.3603	4.0072
2	29.3675	6.4988
4	35.8663	13.1648
8	49.0311	39.6686
25	88.6997	11.3003
38	100	0
64	100	

d60	d10	Cu
12	0.33	36

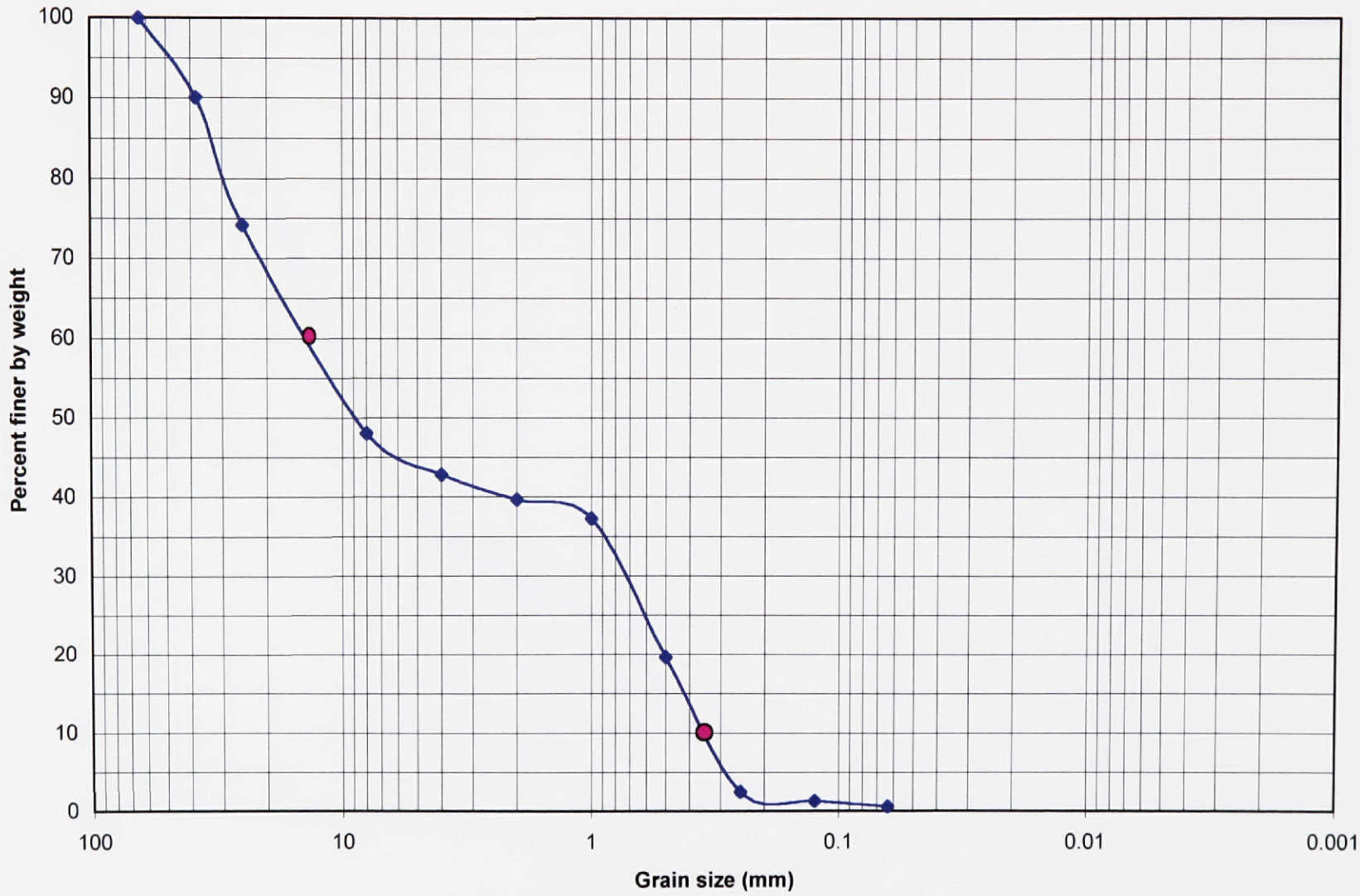

Figure B-5. EE-3 grain size distribution 21 feet below land surface.

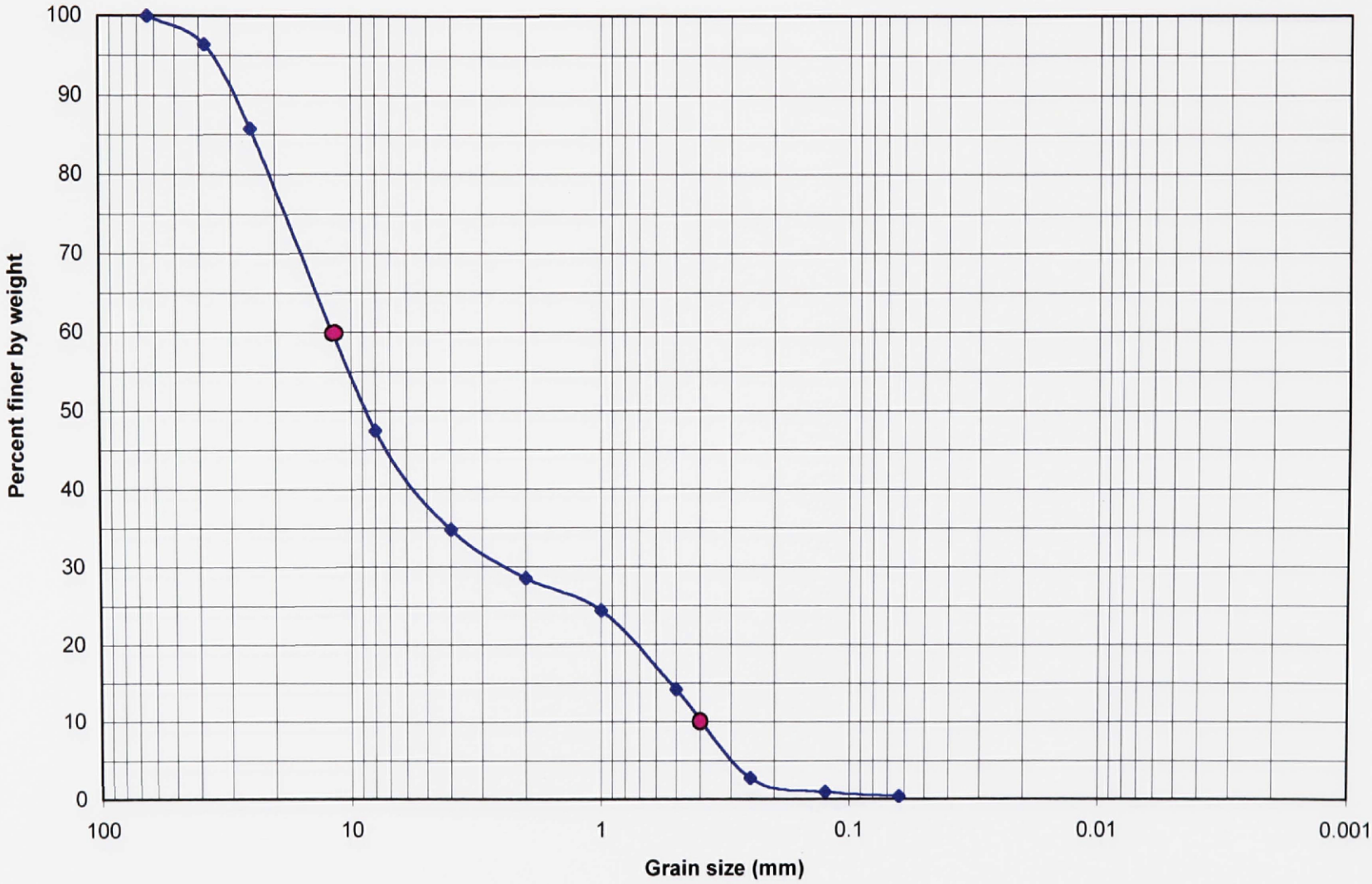

Figure B-6. EE-4 grain size distribution 21 feet below land surface.

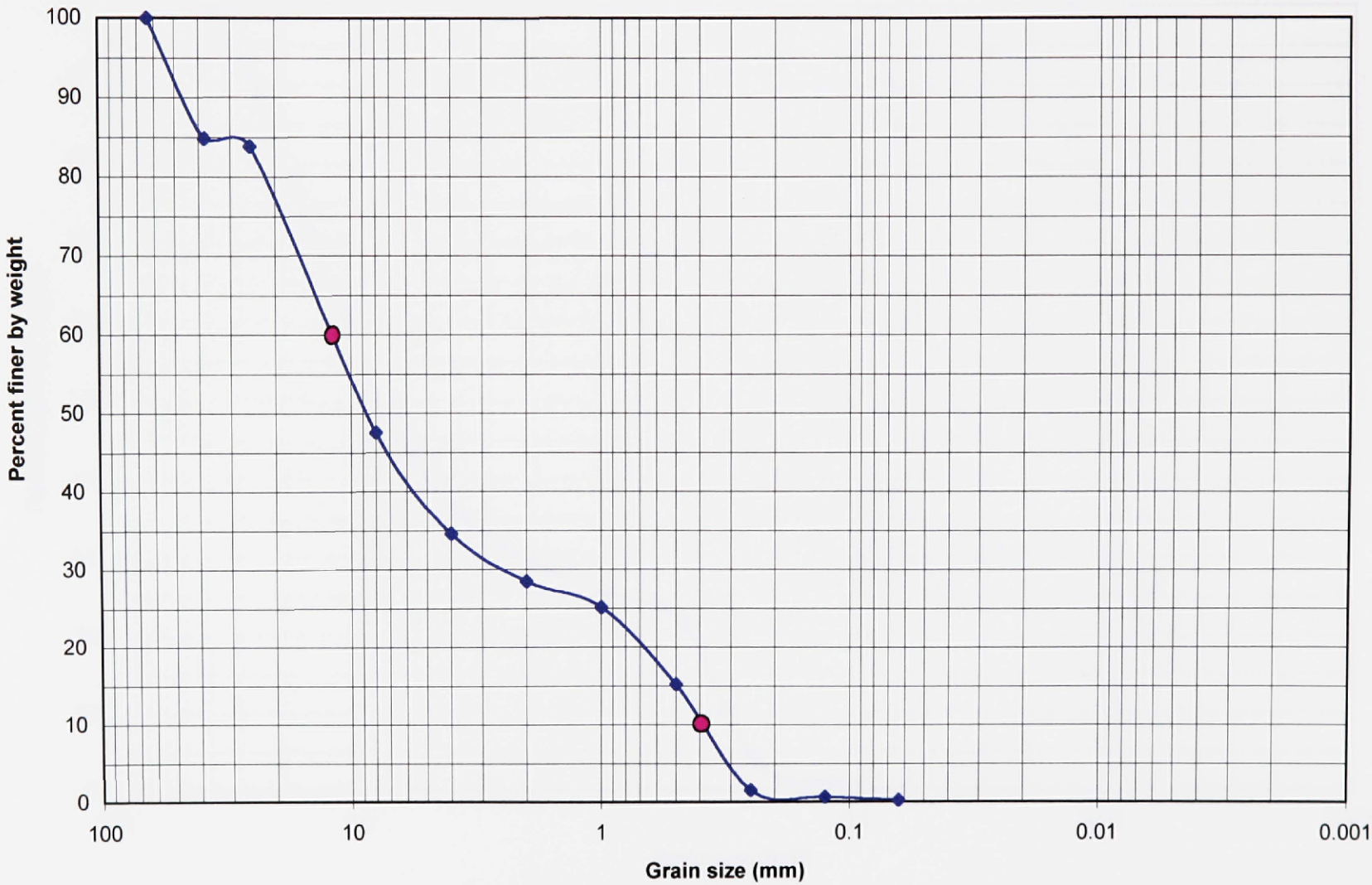

Figure B-7. EE-5 grain size distribution 21 feet below land surface.

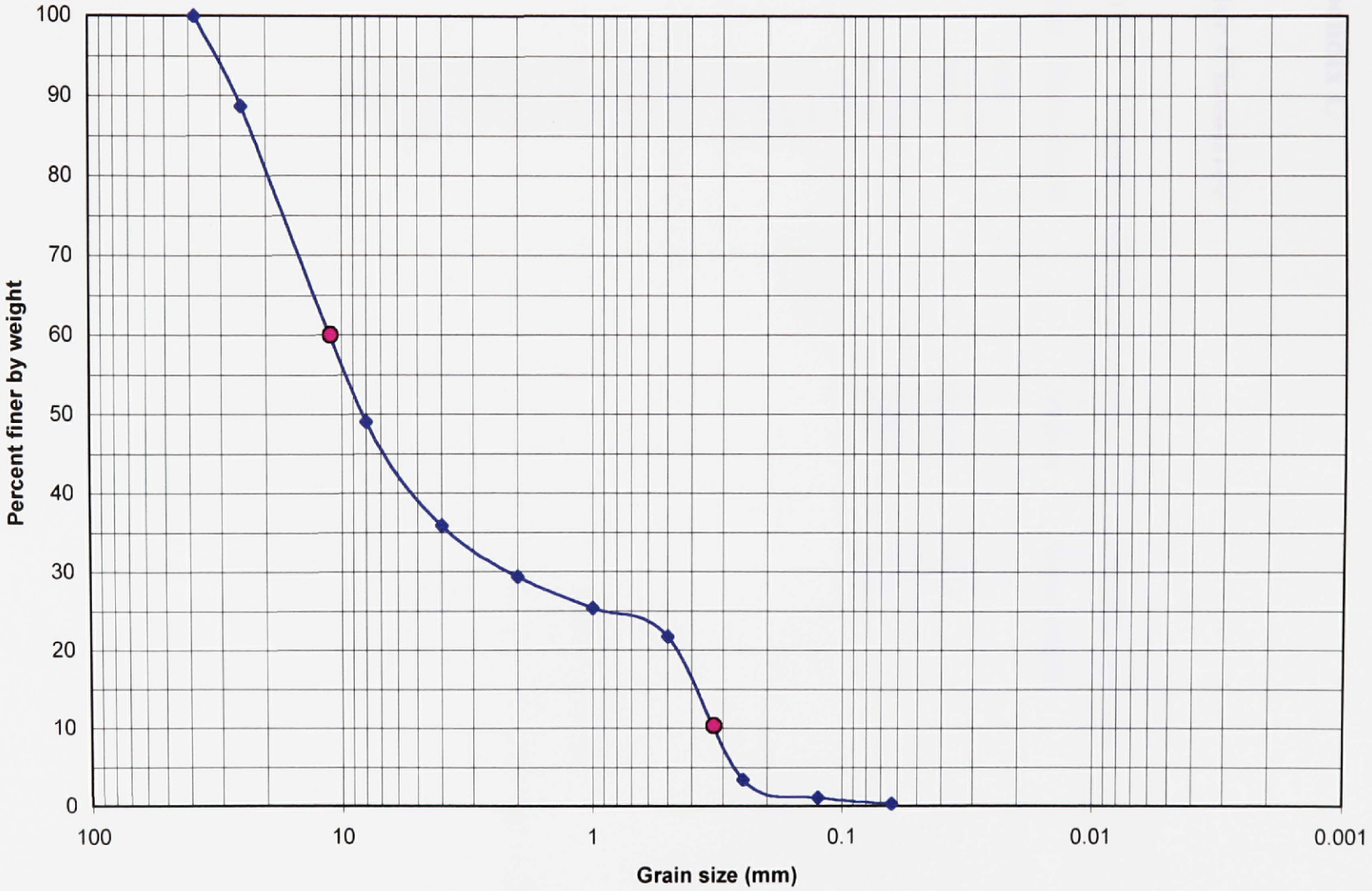

Figure B-8. EE-6 grain size distribution 21 feet below land surface.

Appendix C

Water Chemistry

Table C-1. Complete cation and anion water chemistry analysis.

Cations	Conc. (mg/l)	Anions	Conc. (mg/l)
Ag	N/A	F	0.17
Al	<0.003	Cl	7.29
As	N/A	NO2-N	<0.1
Ba	0.191	NO3-N	0.66
Be	<0.0001	PO4-P	<0.1
Ca	53.68	SO4	16.3
Cd	<0.001		
Co	<0.001		
Cr	<0.005		
Cu	<0.001		
Fe	0.0122		
K	2.33		
Li	0.0037		
Mg	16.87		
Mn	<0.001		
Mo	<0.001		
Na	8.591		
Ni	<0.001		
Pb	<0.004		
S	5.376		
Si	9.947		
Sr	0.1238		
Ti	<0.0005		
V	0.0013		
Zn	0.001		

Appendix D

Aquifer Slug Tests

A total of six slug tests were conducted using an SE 1000C Environmental Logger, three at EE-5 and three at EE-6 (Tables D-1 to D-6). Data were plotted on semi-logarithmic graphs (Figures D-1 to D-6), and used to estimate preliminary hydraulic conductivity values at the site. Since the piezometer length was more than 8 times the well radius, the following Hvorslev equation was applied:

$$K = \frac{[r^2 \ln(Le/R)]}{2LeT_0}$$

r - radius of the well casing

R - radius of the well screen

Le - length of the well screen

$\mathbf{T_0}$ - time it takes for the water level to fall to 37% of the initial change

For all calculations, the radius of the well casing and well screen was 0.125 ft, with the length of the well screen 1.7 ft.

Table D-1. EE-5a slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	7.051	0.1566	6.765
0.0033	7.44	0.16	6.746
0.0066	7.214	0.1633	6.727
0.01	7.011	0.1666	6.708
0.0133	7.187	0.17	6.692
0.0166	7.35	0.1733	6.674
0.02	7.521	0.1766	6.663
0.0233	7.704	0.18	6.654
0.0266	7.923	0.1833	6.639
0.03	8.105	0.1866	6.622
0.0333	8.118	0.19	6.618
0.0366	8.189	0.1933	6.609
0.04	8.346	0.1966	6.592
0.0433	8.318	0.2	6.584
0.0466	8.161	0.2033	6.571
0.05	8.12	0.2066	6.563
0.0533	7.994	0.21	6.554
0.0566	7.962	0.2133	6.549
0.06	7.873	0.2166	6.54
0.0633	7.806	0.22	6.532
0.0666	7.756	0.2233	6.525
0.07	7.72	0.2266	6.518
0.0733	7.688	0.23	6.511
0.0766	7.642	0.2333	6.502
0.08	7.591	0.2366	6.499
0.0833	7.542	0.24	6.494
0.0866	7.485	0.2433	6.488
0.09	7.436	0.2466	6.482
0.0933	7.398	0.25	6.476
0.0966	7.361	0.2533	6.47
0.1	7.313	0.2566	6.466
0.1033	7.266	0.26	6.461
0.1066	7.238	0.2633	6.457
0.11	7.195	0.2666	6.454
0.1133	7.157	0.27	6.449
0.1166	7.116	0.2733	6.442
0.12	7.083	0.2766	6.438
0.1233	7.042	0.28	6.436
0.1266	7.015	0.2833	6.401
0.13	6.974	0.2866	6.398
0.1333	6.944	0.29	6.394
0.1366	6.908	0.2933	6.388
0.14	6.879	0.2966	6.384
0.1433	6.851	0.3	6.381
0.1466	6.834	0.3033	6.377
0.15	6.808	0.3066	6.374
0.1533	6.788	0.31	6.371

Table D-1. EE-5a slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.367	1	6.291
0.3166	6.364	1.2	6.287
0.32	6.361	1.4	6.287
0.3233	6.358	1.6	6.287
0.3266	6.355	1.8	6.287
0.33	6.351	2	6.287
0.3333	6.349	2.2	6.287
0.35	6.343	2.4	6.287
0.3666	6.332	2.6	6.287
0.3833	6.326	2.8	6.287
0.4	6.318	3	6.287
0.4166	6.315	3.2	6.287
0.4333	6.31	3.4	6.287
0.45	6.307	3.6	6.287
0.4666	6.304	3.8	6.287
0.4833	6.301	4	6.287
0.5	6.301	4.2	6.287
0.5166	6.301	4.4	6.287
0.5333	6.297	4.6	6.287
0.55	6.297	4.8	6.287
0.5666	6.297	5	6.287
0.5833	6.294	5.2	6.287
0.6	6.294	5.4	6.287
0.6166	6.294	5.6	6.287
0.6333	6.294	5.8	6.287
0.65	6.294	6	6.287
0.6666	6.294	6.2	6.289
0.6833	6.294	6.4	6.287
0.7	6.294	6.6	6.287
0.7166	6.294	6.8	6.287
0.7333	6.294	7	6.287
0.75	6.294	7.2	6.287
0.7666	6.294	7.4	6.287
0.7833	6.294	7.6	6.287
0.8	6.294	7.8	6.287
0.8166	6.294	8	6.287
0.8333	6.294	8.2	6.287
0.85	6.294	8.4	6.287
0.8666	6.297	8.6	6.287
0.8833	6.294	8.8	6.287
0.9	6.294	9	6.287
0.9166	6.294	9.2	6.287
0.9333	6.291	9.4	6.287
0.95	6.291	9.6	6.287
0.9666	6.291	9.8	6.287
0.9833	6.291	10	6.287

Table D-2. EE-5b slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	6.841	0.1566	6.835
0.0033	7.034	0.16	6.813
0.0066	7.177	0.1633	6.787
0.01	6.661	0.1666	6.768
0.0133	6.724	0.17	6.746
0.0166	6.99	0.1733	6.727
0.02	7.135	0.1766	6.708
0.0233	7.006	0.18	6.692
0.0266	7.344	0.1833	6.673
0.03	7.379	0.1866	6.658
0.0333	7.357	0.19	6.642
0.0366	7.461	0.1933	6.626
0.04	7.569	0.1966	6.613
0.0433	7.784	0.2	6.597
0.0466	7.816	0.2033	6.585
0.05	7.828	0.2066	6.572
0.0533	7.977	0.21	6.56
0.0566	8.018	0.2133	6.547
0.06	8.12	0.2166	6.537
0.0633	8.161	0.22	6.525
0.0666	8.059	0.2233	6.515
0.07	7.98	0.2266	6.506
0.0733	7.901	0.23	6.496
0.0766	7.847	0.2333	6.487
0.08	7.778	0.2366	6.477
0.0833	7.715	0.24	6.471
0.0866	7.651	0.2433	6.461
0.09	7.572	0.2466	6.455
0.0933	7.537	0.25	6.446
0.0966	7.512	0.2533	6.439
0.1	7.433	0.2566	6.433
0.1033	7.376	0.26	6.423
0.1066	7.341	0.2633	6.42
0.11	7.294	0.2666	6.414
0.1133	7.253	0.27	6.408
0.1166	7.211	0.2733	6.401
0.12	7.17	0.2766	6.395
0.1233	7.132	0.28	6.392
0.1266	7.091	0.2833	6.385
0.13	7.063	0.2866	6.379
0.1333	7.028	0.29	6.376
0.1366	6.999	0.2933	6.37
0.14	6.968	0.2966	6.366
0.1433	6.939	0.3	6.363
0.1466	6.911	0.3033	6.357
0.15	6.885	0.3066	6.354
0.1533	6.86	0.31	6.351

Table D-2. EE-5b slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.347	1	6.256
0.3166	6.344	1.2	6.256
0.32	6.341	1.4	6.256
0.3233	6.338	1.6	6.256
0.3266	6.335	1.8	6.256
0.33	6.332	2	6.256
0.3333	6.328	2.2	6.256
0.35	6.313	2.4	6.256
0.3666	6.303	2.6	6.256
0.3833	6.294	2.8	6.256
0.4	6.287	3	6.256
0.4166	6.281	3.2	6.256
0.4333	6.278	3.4	6.256
0.45	6.272	3.6	6.259
0.4666	6.268	3.8	6.256
0.4833	6.268	4	6.256
0.5	6.265	4.2	6.256
0.5166	6.262	4.4	6.256
0.5333	6.262	4.6	6.256
0.55	6.262	4.8	6.256
0.5666	6.262	5	6.256
0.5833	6.259	5.2	6.256
0.6	6.259	5.4	6.256
0.6166	6.259	5.6	6.256
0.6333	6.259	5.8	6.256
0.65	6.259	6	6.256
0.6666	6.259	6.2	6.256
0.6833	6.259	6.4	6.256
0.7	6.259	6.6	6.256
0.7166	6.259	6.8	6.256
0.7333	6.256	7	6.256
0.75	6.256	7.2	6.256
0.7666	6.256	7.4	6.256
0.7833	6.256	7.6	6.256
0.8	6.256	7.8	6.256
0.8166	6.256	8	6.256
0.8333	6.256	8.2	6.256
0.85	6.256	8.4	6.256
0.8666	6.256	8.6	6.256
0.8833	6.259	8.8	6.256
0.9	6.256	9	6.256
0.9166	6.256	9.2	6.256
0.9333	6.256	9.4	6.256
0.95	6.256	9.6	6.256
0.9666	6.256	9.8	6.256
0.9833	6.256	10	6.256

Table D-3. EE-5c slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	7.705	0.1566	6.772
0.0033	7.98	0.16	6.753
0.0066	7.67	0.1633	6.737
0.01	7.287	0.1666	6.718
0.0133	7.366	0.17	6.705
0.0166	7.686	0.1733	6.683
0.02	7.911	0.1766	6.673
0.0233	8.218	0.18	6.661
0.0266	8.465	0.1833	6.648
0.03	8.49	0.1866	6.632
0.0333	8.493	0.19	6.62
0.0366	8.357	0.1933	6.61
0.04	8.281	0.1966	6.597
0.0433	8.186	0.2	6.588
0.0466	8.11	0.2033	6.575
0.05	8.034	0.2066	6.566
0.0533	7.961	0.21	6.556
0.0566	7.873	0.2133	6.55
0.06	7.828	0.2166	6.541
0.0633	7.762	0.22	6.534
0.0666	7.699	0.2233	6.525
0.07	7.639	0.2266	6.518
0.0733	7.585	0.23	6.509
0.0766	7.534	0.2333	6.496
0.08	7.471	0.2366	6.493
0.0833	7.42	0.24	6.484
0.0866	7.392	0.2433	6.477
0.09	7.347	0.2466	6.471
0.0933	7.303	0.25	6.465
0.0966	7.265	0.2533	6.458
0.1	7.224	0.2566	6.455
0.1033	7.189	0.26	6.449
0.1066	7.154	0.2633	6.442
0.11	7.12	0.2666	6.439
0.1133	7.088	0.27	6.433
0.1166	7.056	0.2733	6.427
0.12	7.028	0.2766	6.423
0.1233	6.999	0.28	6.42
0.1266	6.974	0.2833	6.414
0.13	6.946	0.2866	6.411
0.1333	6.92	0.29	6.408
0.1366	6.898	0.2933	6.401
0.14	6.873	0.2966	6.398
0.1433	6.851	0.3	6.395
0.1466	6.828	0.3033	6.392
0.15	6.809	0.3066	6.389
0.1533	6.791	0.31	6.385

Table D-3. EE-5c slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.382	1	6.297
0.3166	6.379	1.2	6.294
0.32	6.376	1.4	6.297
0.3233	6.373	1.6	6.294
0.3266	6.37	1.8	6.294
0.33	6.366	2	6.294
0.3333	6.363	2.2	6.294
0.35	6.354	2.4	6.294
0.3666	6.341	2.6	6.294
0.3833	6.335	2.8	6.294
0.4	6.325	3	6.294
0.4166	6.322	3.2	6.294
0.4333	6.316	3.4	6.294
0.45	6.313	3.6	6.294
0.4666	6.31	3.8	6.294
0.4833	6.306	4	6.294
0.5	6.306	4.2	6.294
0.5166	6.303	4.4	6.294
0.5333	6.303	4.6	6.294
0.55	6.303	4.8	6.294
0.5666	6.3	5	6.294
0.5833	6.3	5.2	6.294
0.6	6.3	5.4	6.294
0.6166	6.3	5.6	6.294
0.6333	6.297	5.8	6.294
0.65	6.297	6	6.294
0.6666	6.297	6.2	6.294
0.6833	6.297	6.4	6.294
0.7	6.297	6.6	6.294
0.7166	6.297	6.8	6.294
0.7333	6.297	7	6.294
0.75	6.297	7.2	6.294
0.7666	6.297	7.4	6.294
0.7833	6.297	7.6	6.294
0.8	6.297	7.8	6.294
0.8166	6.297	8	6.294
0.8333	6.297	8.2	6.294
0.85	6.297	8.4	6.294
0.8666	6.297	8.6	6.294
0.8833	6.297	8.8	6.294
0.9	6.297	9	6.294
0.9166	6.297	9.2	6.294
0.9333	6.294	9.4	6.294
0.95	6.297	9.6	6.294
0.9666	6.297	9.8	6.294
0.9833	6.297	10	6.294

Table D-4. EE-6a slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	7.554	0.1566	6.526
0.0033	7.754	0.16	6.52
0.0066	7.678	0.1633	6.516
0.01	7.368	0.1666	6.513
0.0133	7.605	0.17	6.507
0.0166	7.732	0.1733	6.504
0.02	7.643	0.1766	6.501
0.0233	8.159	0.18	6.497
0.0266	8.374	0.1833	6.494
0.03	8.285	0.1866	6.491
0.0333	8.175	0.19	6.488
0.0366	8.108	0.1933	6.488
0.04	7.963	0.1966	6.485
0.0433	7.833	0.2	6.482
0.0466	7.719	0.2033	6.482
0.05	7.611	0.2066	6.478
0.0533	7.513	0.21	6.478
0.0566	7.428	0.2133	6.475
0.06	7.333	0.2166	6.475
0.0633	7.257	0.22	6.475
0.0666	7.184	0.2233	6.472
0.07	7.118	0.2266	6.472
0.0733	7.08	0.23	6.472
0.0766	7.013	0.2333	6.469
0.08	6.956	0.2366	6.469
0.0833	6.909	0.24	6.469
0.0866	6.861	0.2433	6.469
0.09	6.833	0.2466	6.469
0.0933	6.801	0.25	6.466
0.0966	6.773	0.2533	6.466
0.1	6.744	0.2566	6.466
0.1033	6.722	0.26	6.466
0.1066	6.7	0.2633	6.466
0.11	6.678	0.2666	6.466
0.1133	6.659	0.27	6.466
0.1166	6.643	0.2733	6.466
0.12	6.63	0.2766	6.463
0.1233	6.615	0.28	6.463
0.1266	6.602	0.2833	6.463
0.13	6.589	0.2866	6.463
0.1333	6.58	0.29	6.463
0.1366	6.57	0.2933	6.463
0.14	6.561	0.2966	6.463
0.1433	6.551	0.3	6.463
0.1466	6.545	0.3033	6.463
0.15	6.539	0.3066	6.463
0.1533	6.532	0.31	6.463

Table D-4. EE-6a slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.463	1	6.46
0.3166	6.463	1.2	6.46
0.32	6.463	1.4	6.46
0.3233	6.463	1.6	6.46
0.3266	6.463	1.8	6.46
0.33	6.463	2	6.46
0.3333	6.463	2.2	6.46
0.35	6.463	2.4	6.46
0.3666	6.463	2.6	6.46
0.3833	6.46	2.8	6.46
0.4	6.46	3	6.46
0.4166	6.46	3.2	6.46
0.4333	6.46	3.4	6.46
0.45	6.46	3.6	6.46
0.4666	6.46	3.8	6.46
0.4833	6.46	4	6.456
0.5	6.46	4.2	6.46
0.5166	6.46	4.4	6.456
0.5333	6.46	4.6	6.46
0.55	6.46	4.8	6.46
0.5666	6.46	5	6.46
0.5833	6.46	5.2	6.46
0.6	6.46	5.4	6.46
0.6166	6.46	5.6	6.456
0.6333	6.46	5.8	6.456
0.65	6.46	6	6.456
0.6666	6.46	6.2	6.46
0.6833	6.46	6.4	6.46
0.7	6.46	6.6	6.46
0.7166	6.46	6.8	6.456
0.7333	6.46	7	6.456
0.75	6.46	7.2	6.456
0.7666	6.46	7.4	6.46
0.7833	6.46	7.6	6.456
0.8	6.46	7.8	6.46
0.8166	6.46	8	6.456
0.8333	6.46	8.2	6.456
0.85	6.46	8.4	6.46
0.8666	6.46	8.6	6.456
0.8833	6.46	8.8	6.46
0.9	6.46	9	6.456
0.9166	6.46	9.2	6.456
0.9333	6.46	9.4	6.46
0.95	6.46	9.6	6.46
0.9666	6.46	9.8	6.456
0.9833	6.46	10	6.456

Table D-5. EE-6b slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	7.627	0.1566	6.529
0.0033	8.368	0.16	6.526
0.0066	8.308	0.1633	6.52
0.01	8.01	0.1666	6.516
0.0133	7.893	0.17	6.51
0.0166	7.89	0.1733	6.507
0.02	8.013	0.1766	6.504
0.0233	8.244	0.18	6.501
0.0266	8.311	0.1833	6.497
0.03	8.327	0.1866	6.494
0.0333	8.165	0.19	6.491
0.0366	8.048	0.1933	6.488
0.04	7.931	0.1966	6.488
0.0433	7.811	0.2	6.485
0.0466	7.687	0.2033	6.482
0.05	7.58	0.2066	6.482
0.0533	7.501	0.21	6.478
0.0566	7.39	0.2133	6.478
0.06	7.311	0.2166	6.475
0.0633	7.263	0.22	6.472
0.0666	7.175	0.2233	6.472
0.07	7.118	0.2266	6.472
0.0733	7.051	0.23	6.472
0.0766	6.988	0.2333	6.472
0.08	6.956	0.2366	6.469
0.0833	6.912	0.24	6.469
0.0866	6.871	0.2433	6.469
0.09	6.836	0.2466	6.466
0.0933	6.804	0.25	6.466
0.0966	6.776	0.2533	6.466
0.1	6.751	0.2566	6.466
0.1033	6.725	0.26	6.466
0.1066	6.703	0.2633	6.463
0.11	6.684	0.2666	6.463
0.1133	6.665	0.27	6.466
0.1166	6.649	0.2733	6.463
0.12	6.634	0.2766	6.463
0.1233	6.618	0.28	6.463
0.1266	6.605	0.2833	6.463
0.13	6.596	0.2866	6.463
0.1333	6.586	0.29	6.463
0.1366	6.573	0.2933	6.463
0.14	6.564	0.2966	6.463
0.1433	6.558	0.3	6.463
0.1466	6.548	0.3033	6.463
0.15	6.542	0.3066	6.463
0.1533	6.535	0.31	6.463

Table D-5. EE-6b slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.463	1	6.456
0.3166	6.463	1.2	6.456
0.32	6.46	1.4	6.456
0.3233	6.46	1.6	6.456
0.3266	6.46	1.8	6.456
0.33	6.46	2	6.456
0.3333	6.46	2.2	6.456
0.35	6.46	2.4	6.456
0.3666	6.46	2.6	6.456
0.3833	6.46	2.8	6.456
0.4	6.46	3	6.456
0.4166	6.46	3.2	6.456
0.4333	6.456	3.4	6.456
0.45	6.46	3.6	6.456
0.4666	6.456	3.8	6.456
0.4833	6.456	4	6.456
0.5	6.46	4.2	6.456
0.5166	6.456	4.4	6.456
0.5333	6.456	4.6	6.456
0.55	6.456	4.8	6.456
0.5666	6.456	5	6.456
0.5833	6.46	5.2	6.456
0.6	6.456	5.4	6.456
0.6166	6.456	5.6	6.456
0.6333	6.46	5.8	6.456
0.65	6.456	6	6.456
0.6666	6.456	6.2	6.456
0.6833	6.456	6.4	6.456
0.7	6.456	6.6	6.456
0.7166	6.456	6.8	6.456
0.7333	6.456	7	6.456
0.75	6.456	7.2	6.456
0.7666	6.456	7.4	6.456
0.7833	6.456	7.6	6.456
0.8	6.456	7.8	6.456
0.8166	6.456	8	6.456
0.8333	6.456	8.2	6.456
0.85	6.456	8.4	6.456
0.8666	6.456	8.6	6.456
0.8833	6.456	8.8	6.456
0.9	6.456	9	6.456
0.9166	6.456	9.2	6.456
0.9333	6.456	9.4	6.456
0.95	6.456	9.6	6.456
0.9666	6.456	9.8	6.456
0.9833	6.456	10	6.456
		12	6.456

Table D-6. EE-6c slug test data.

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0	8.458	0.1566	6.828
0.0033	6.841	0.16	6.806
0.0066	7.353	0.1633	6.787
0.01	7.584	0.1666	6.768
0.0133	7.837	0.17	6.749
0.0166	7.929	0.1733	6.73
0.02	8.334	0.1766	6.711
0.0233	8.284	0.18	6.695
0.0266	8.113	0.1833	6.676
0.03	8.094	0.1866	6.66
0.0333	8.034	0.19	6.641
0.0366	7.986	0.1933	6.625
0.04	7.954	0.1966	6.609
0.0433	7.901	0.2	6.594
0.0466	7.847	0.2033	6.578
0.05	7.796	0.2066	6.562
0.0533	7.755	0.21	6.549
0.0566	7.72	0.2133	6.534
0.06	7.666	0.2166	6.521
0.0633	7.628	0.22	6.505
0.0666	7.584	0.2233	6.492
0.07	7.549	0.2266	6.48
0.0733	7.511	0.23	6.467
0.0766	7.477	0.2333	6.451
0.08	7.439	0.2366	6.442
0.0833	7.407	0.24	6.429
0.0866	7.372	0.2433	6.416
0.09	7.341	0.2466	6.404
0.0933	7.309	0.25	6.391
0.0966	7.277	0.2533	6.378
0.1	7.249	0.2566	6.369
0.1033	7.22	0.26	6.356
0.1066	7.189	0.2633	6.347
0.11	7.163	0.2666	6.334
0.1133	7.135	0.27	6.325
0.1166	7.106	0.2733	6.315
0.12	7.081	0.2766	6.306
0.1233	7.056	0.28	6.293
0.1266	7.03	0.2833	6.284
0.13	7.005	0.2866	6.274
0.1333	6.983	0.29	6.265
0.1366	6.958	0.2933	6.255
0.14	6.932	0.2966	6.246
0.1433	6.913	0.3	6.236
0.1466	6.891	0.3033	6.227
0.15	6.869	0.3066	6.22
0.1533	6.847	0.31	6.211

Table D-6. EE-6c slug test data (cont).

Elapsed time (s)	Input head (ft)	Elapsed time (s)	Input head (ft)
0.3133	6.201	1.2	5.559
0.3166	6.195	1.4	5.553
0.32	6.185	1.6	5.549
0.3233	6.176	1.8	5.549
0.3266	6.17	2	5.549
0.33	6.16	2.2	5.549
0.3333	6.154	2.4	5.549
0.35	6.113	2.6	5.549
0.3666	6.075	2.8	5.549
0.3833	6.04	3	5.546
0.4	6.008	3.2	5.549
0.4166	5.977	3.4	5.549
0.4333	5.948	3.6	5.549
0.45	5.923	3.8	5.549
0.4666	5.897	4	5.546
0.4833	5.875	4.2	5.546
0.5	5.853	4.4	5.546
0.5166	5.834	4.6	5.549
0.5333	5.815	4.8	5.546
0.55	5.796	5	5.546
0.5666	5.78	5.2	5.546
0.5833	5.765	5.4	5.546
0.6	5.749	5.6	5.546
0.6166	5.736	5.8	5.546
0.6333	5.723	6	5.546
0.65	5.711	6.2	5.546
0.6666	5.698	6.4	5.546
0.6833	5.689	6.6	5.546
0.7	5.679	6.8	5.546
0.7166	5.67	7	5.546
0.7333	5.663	7.2	5.546
0.75	5.654	7.4	5.546
0.7666	5.647	7.6	5.546
0.7833	5.638	7.8	5.549
0.8	5.632	8	5.549
0.8166	5.628	8.2	5.549
0.8333	5.622	8.4	5.546
0.85	5.616	8.6	5.549
0.8666	5.613	8.8	5.546
0.8833	5.606	9	5.549
0.9	5.603	9.2	5.546
0.9166	5.6	9.4	5.549
0.9333	5.597	9.6	5.546
0.95	5.594	9.8	5.546
0.9666	5.591	10	5.546
0.9833	5.587	12	5.549
1	5.584	14	5.546

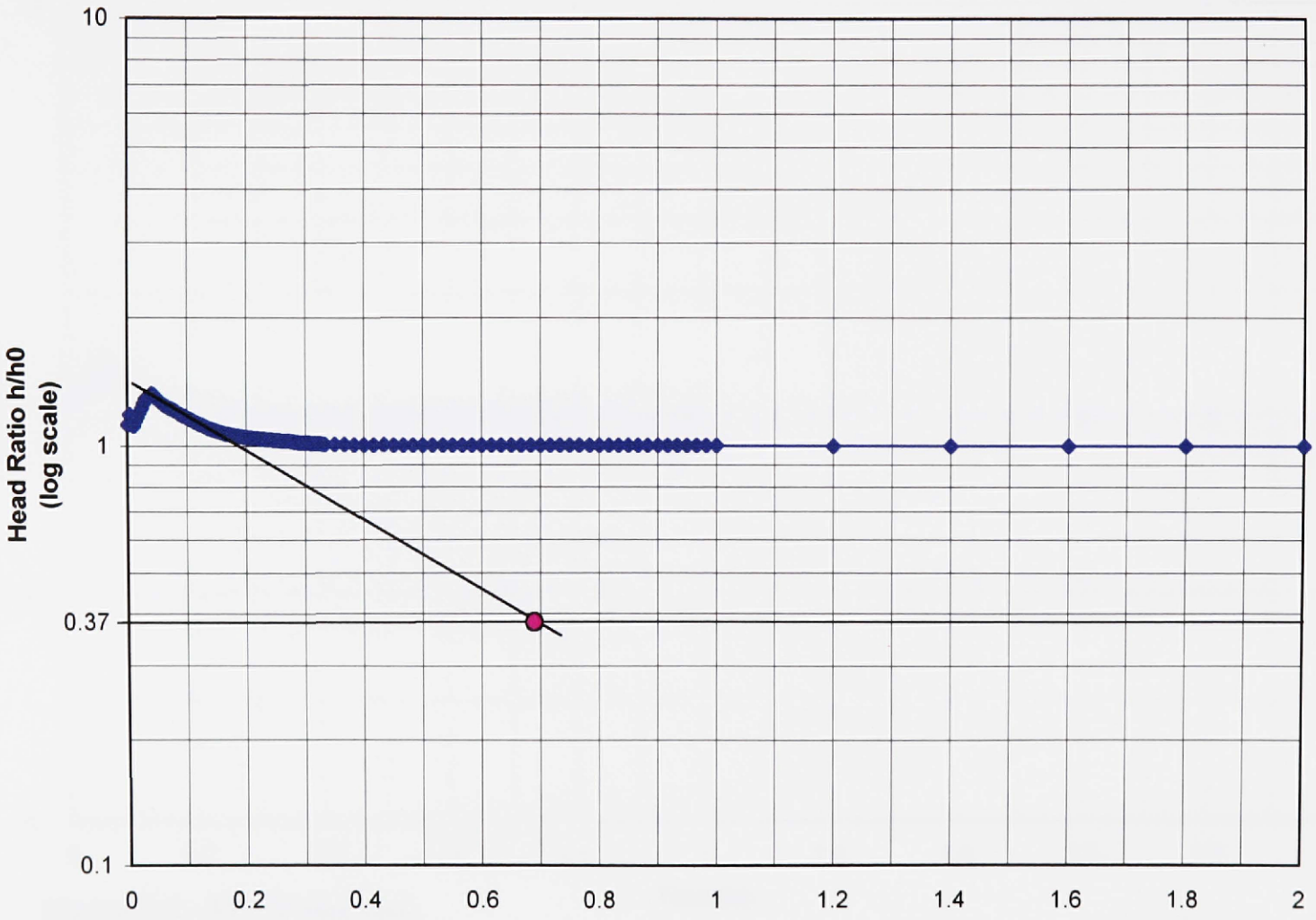

Figure D-1. EE-5a slug test.

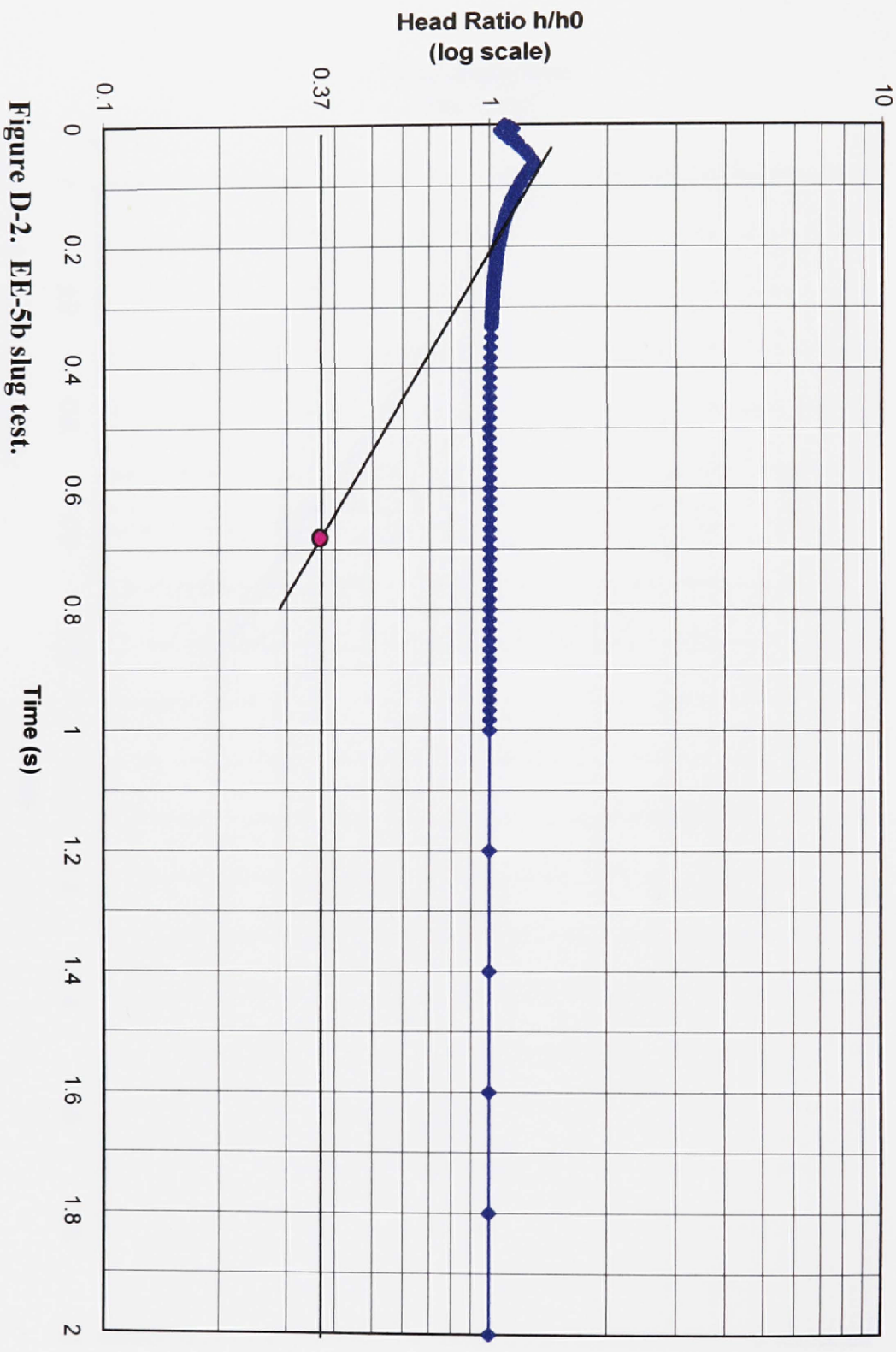

Figure D-2. EE-5b slug test.

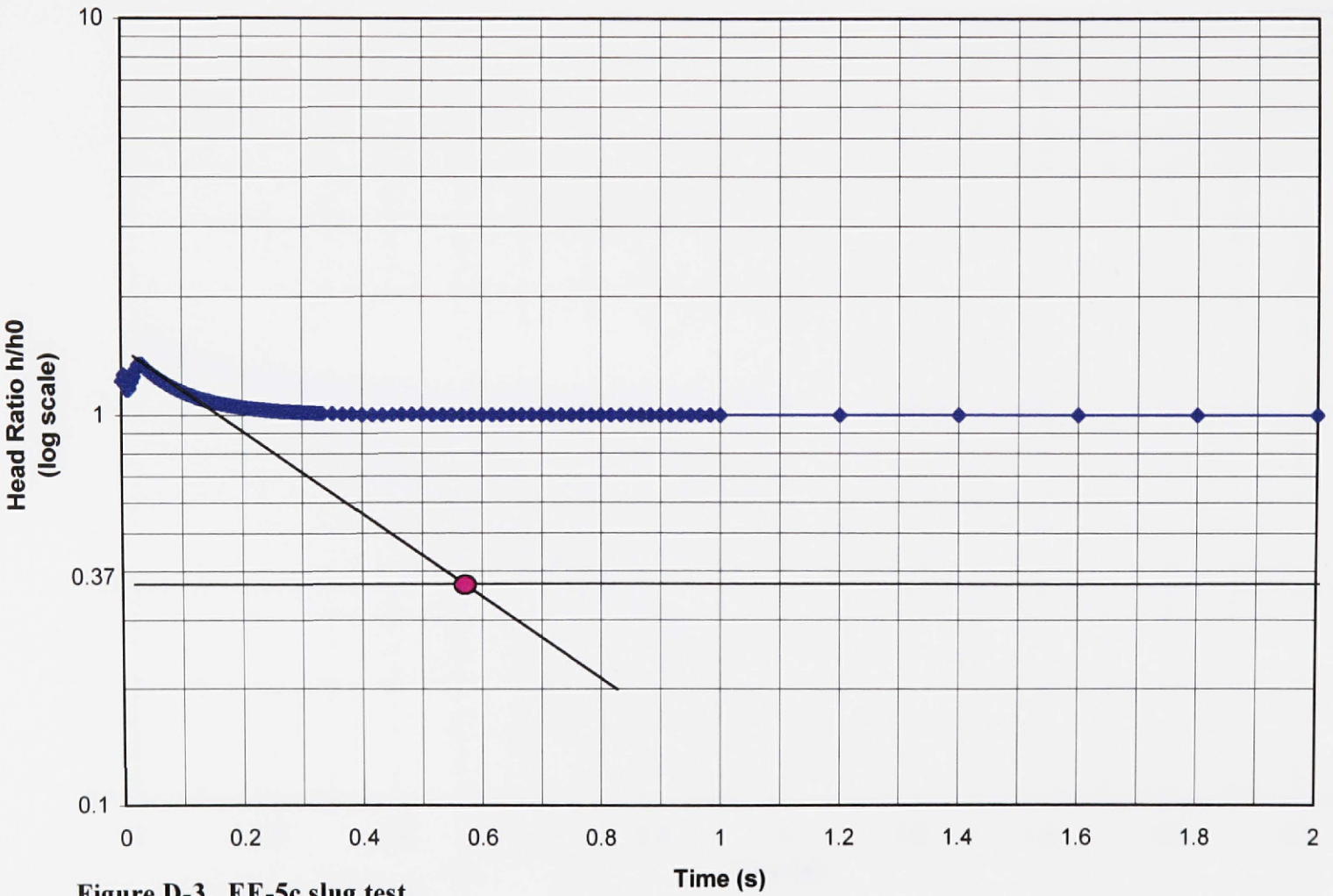

Figure D-3. EE-5c slug test.

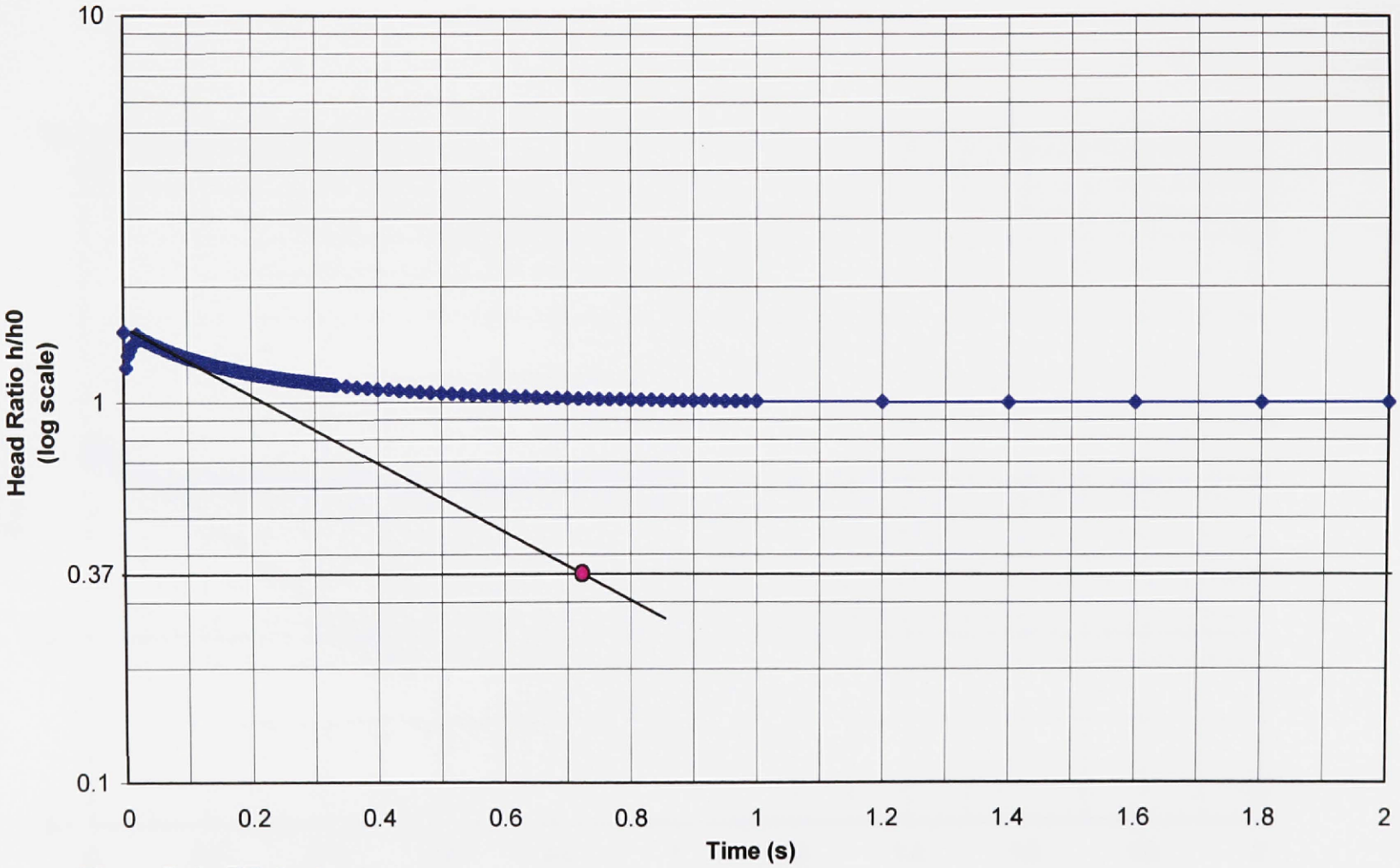

Figure D-6. EE-6c slug test.

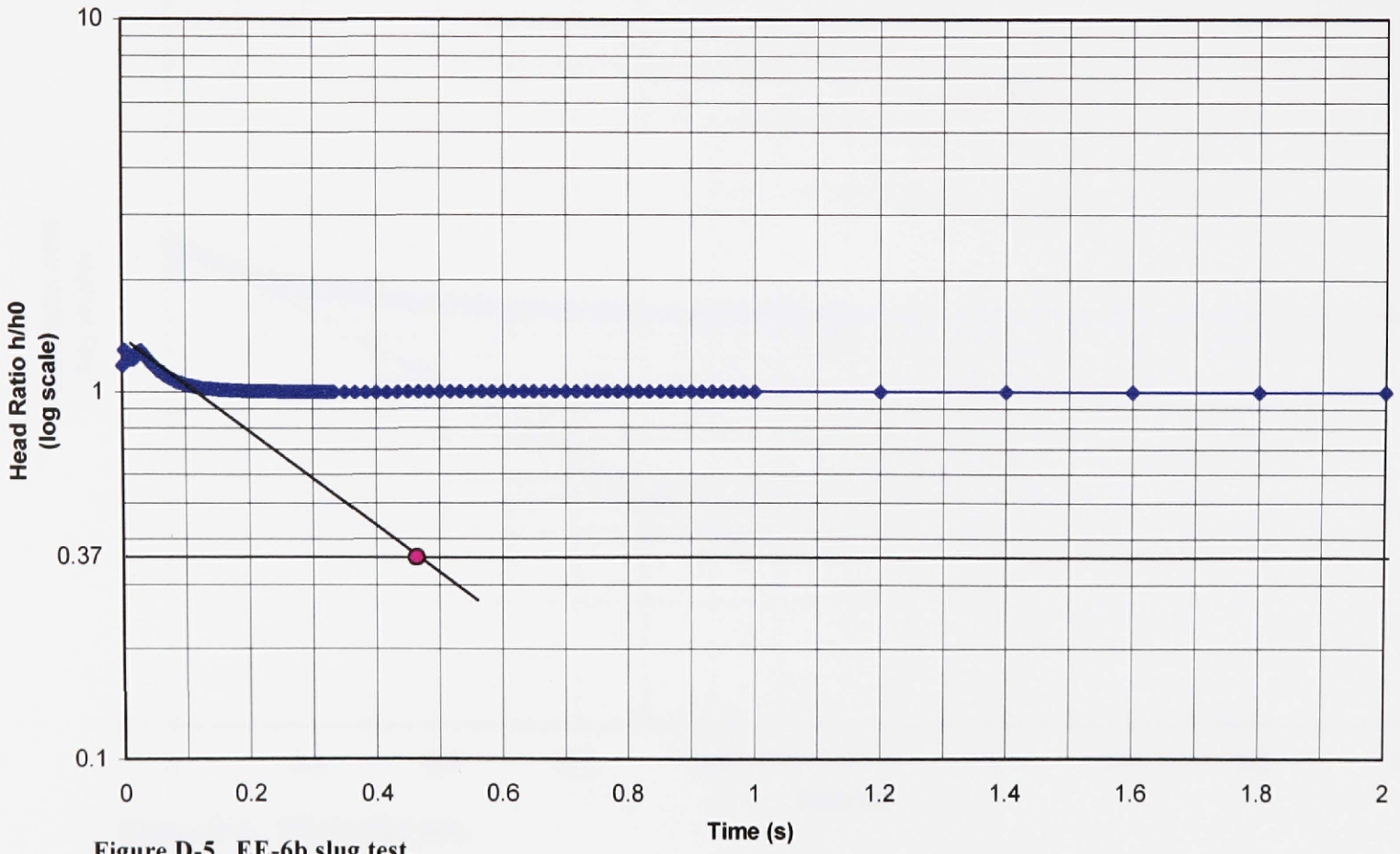

Figure D-5. EE-6b slug test.

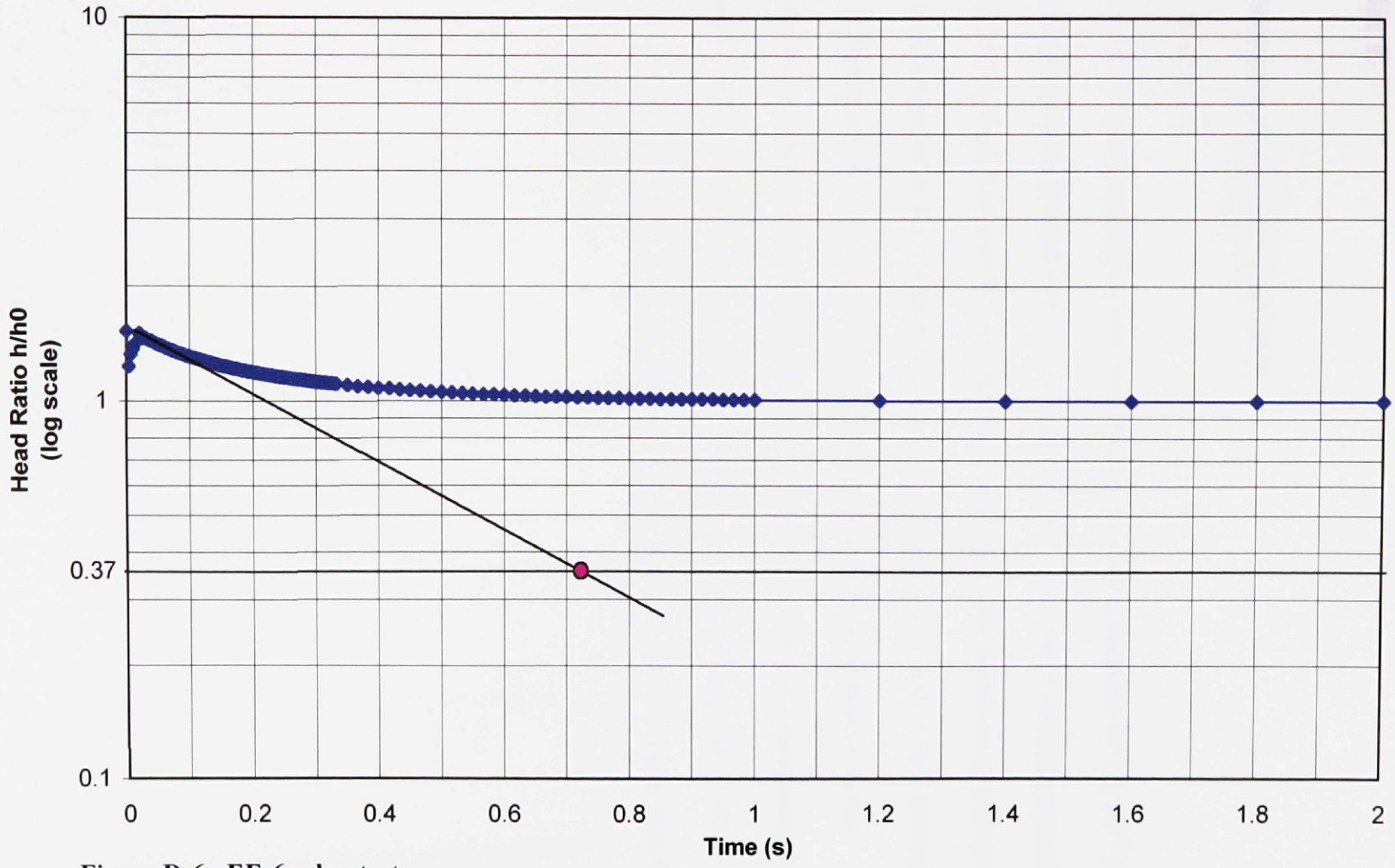

Figure D-6. EE-6c slug test.

Appendix E

MS-2 Bacteriophage Tracer Test

Injection Well I-4

The MS-2 bacteriophage tracer was diluted to a concentration of 1 x 10^{12} PFU/ml, using water from a background well at the Erskine site. The tracer solution was then gravity fed over a 5-minute period into injection well I-4. The initial concentration in the injection well, sampled at I-4 immediately after injection, was 2.45E x 10^{10} PFU/ml. Figure E-1 illustrates the MS-2 coliphage level dropping off very steeply as the groundwater moves the unabsorbed viruses out of the area. The remaining adsorbed viruses leach over a long period of time, resulting in the long, trailing tail, with a concentration of 1E x10^{6} PFU/ml after 468 hours (Figure E-2). MS-2 tracer data for all wells are listed in Table E-1.

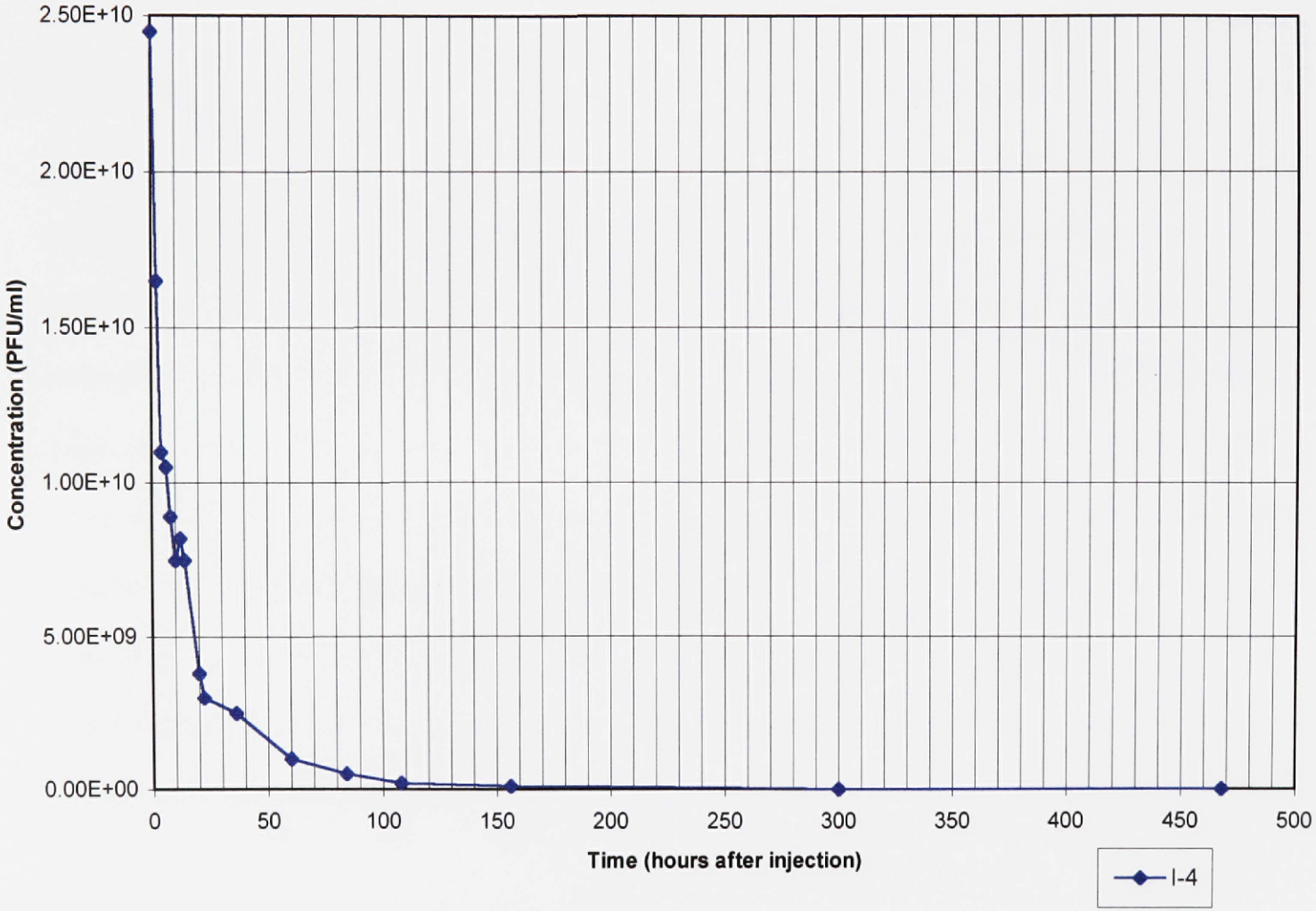

Figure E-1. MS-2 tracer analysis at injection well I-4.

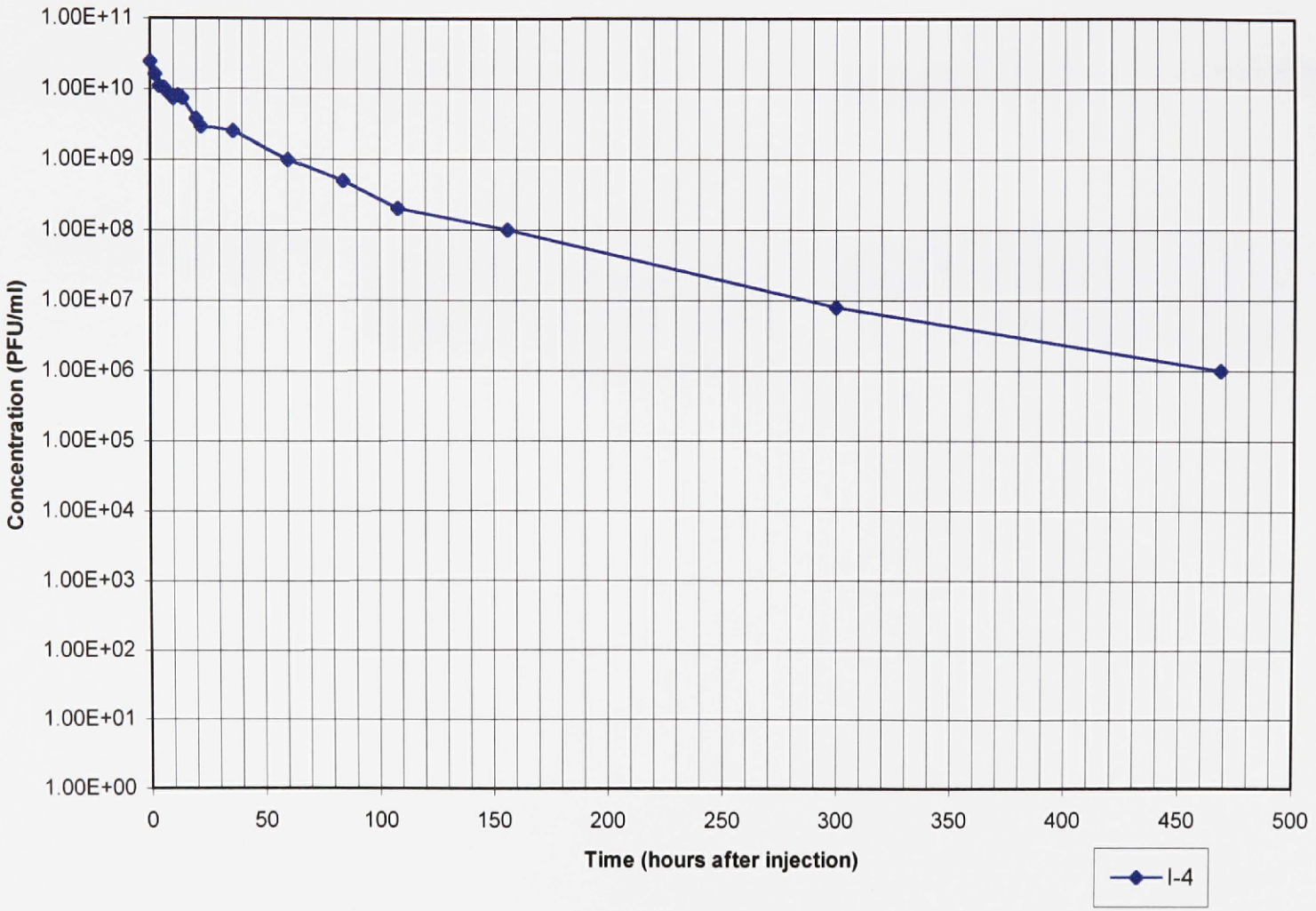

Figure E-2. MS-2 tracer analysis at injection well I-4.

Table E-1. MS-2 tracer test data.

Well	Time (hrs)	Conc. (PFU/ml)
I-4	0	2.45E+10
I-4	2	1.65E+10
I-4	4	1.10E+10
I-4	6	1.05E+10
I-4	8	8.90E+09
I-4	10	7.50E+09
I-4	12	8.20E+09
I-4	14	7.50E+09
I-4	20	3.80E+09
I-4	22	3.00E+09
I-4	36	2.50E+09
I-4	60	1.00E+09
I-4	84	5.00E+08
I-4	108	2.00E+08
I-4	156	1.00E+08
I-4	300	8.00E+06
I-4	468	1.00E+06
P-24	0	0
P-24	2	1.75E+06
P-24	4	9.00E+06
P-24	6	1.38E+07
P-24	8	1.40E+07
P-24	10	1.18E+07
P-24	12	1.12E+07
P-24	14	1.18E+07
P-24	16	9.30E+06
P-24	18	1.25E+07
P-24	20	1.50E+07
P-24	22	1.60E+07
P-24	24	1.20E+07
P-24	34	8.20E+06
P-24	36	7.80E+06
P-25	0	0
P-25	2	0
P-25	4	60
P-25	6	103
P-25	8	87
P-25	10	110
P-25	14	50
P-25	18	20
P-25	22	12
P-25	34	3
P-25	36	5
P-30	0	0
P-30	2	0
P-30	4	0
P-30	6	0

Table E-1. MS-2 tracer test data (cont).

Well	Time (hrs)	Conc. (PFU/ml)
P-30	8	0
P-30	10	4.00E+01
P-30	14	5.00E+02
P-30	16	1.50E+03
P-30	18	3.00E+03
P-30	20	3.50E+03
P-30	22	5.00E+03
P-30	24	2.00E+03
P-30	36	9.00E+02
P-30	60	1.20E+02
P-31	0	0
P-31	2	0.00E+00
P-31	4	0.00E+00
P-31	6	0.00E+00
P-31	8	0.00E+00
P-31	10	2.50E+06
P-31	12	4.80E+06
P-31	14	6.90E+06
P-31	16	7.80E+06
P-31	18	6.20E+06
P-31	20	5.80E+06
P-31	22	4.80E+06
P-31	24	4.00E+06
P-31	34	9.00E+05
P-31	36	1.00E+06
P-31	60	3.00E+05
P-32	0	0
P-32	2	0
P-32	4	0
P-32	6	0
P-32	8	0
P-32	10	0
P-32	12	0
P-32	14	1.51E+04
P-32	16	2.52E+04
P-32	18	1.75E+04
P-32	20	1.50E+04
P-32	22	2.15E+04
P-32	24	9.00E+03
P-32	34	1.10E+04
P-32	36	4.70E+03
P-32	60	3.50E+03
P-32	68	2.00E+03
P-35	36	15
P-35	40	68
P-35	60	140
P-35	68	120

Table E-1. MS-2 tracer test data (cont).

Well	Time (hrs)	Conc. (PFU/ml)
P-35	84	62
P-35	108	16
P-35	132	25
P-35	156	21
P-35	180	13
P-36	36	5
P-36	40	4
P-36	60	0.4
P-36	68	0.5
P-36	84	0.6
P-36	108	0.7
P-36	132	40
P-36	156	0.3
P-36	180	0.5
P-37	36	100
P-37	40	600
P-37	60	1800
P-37	68	2200
P-37	84	1250
P-37	108	400
P-37	132	110
P-37	156	100
P-37	180	90